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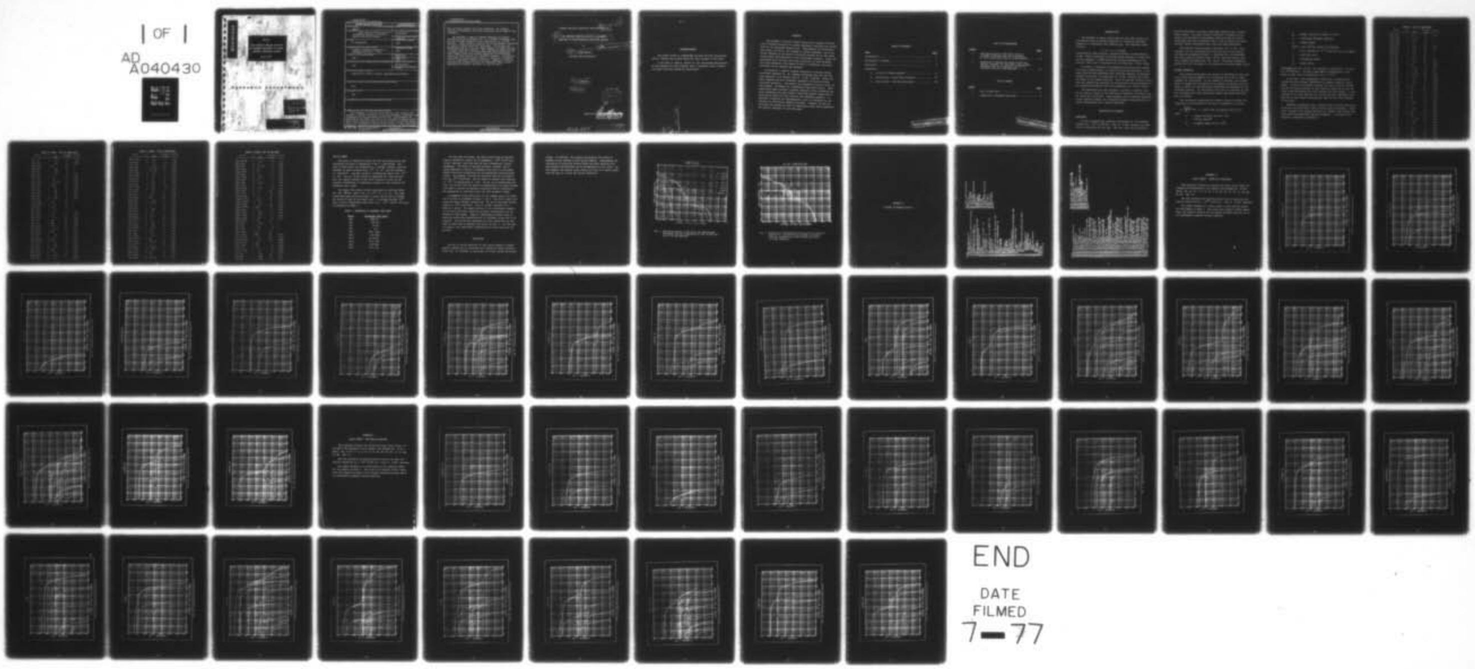

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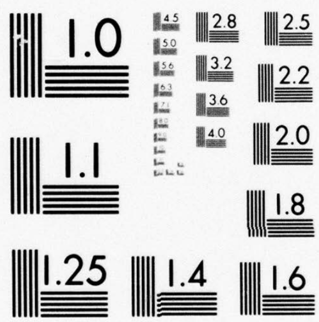

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FAST NEUTRON INDUCED ACTIVITY OF ELEMENTS RELEVANT TO FUSION REACTOR STRUCTURAL DESIGN

April 1977

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The designer of nuclear fusion devices must consider the problem of induced activation of system components resulting from irradiation by the generated neutron flux. Requirements for maintenance and repair, as well as for storage of exposed equipment, can be directly affected by the levels of activity induced and by the radioactive decay characteristics of the constituent elements. Since the activation cross sections and decay proper-

ties of these elements have been tabulated, the induced activity of different structural materials can be computed and analyzed.

We describe a computer program developed to catalog isotopic activities obtained for 19 elements following seven day and one year exposures to an intense flux of 14 MeV neutrons. These elements comprise the most prominent components of reactor-related structural materials. The results are presented as decay curves for each element, including the contributions from each isotope. This compilation makes possible a graphic analysis of the activation and decay properties for each element listed and permits comparison of anticipated levels of total activity for different elements. In addition, activation of representative alloys is simulated by combination of constituent element activities. Examples of this application are present in plots of radioactive decay curves generated for Inconel, Nitronic 33, and 304 steel.

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E. A. Kamykowski

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Director of Research

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ABSTRACT

The designer of nuclear fusion devices must consider the problem of induced activation of system components resulting from irradiation by the generated neutron flux. Requirements for maintenance and repair, as well as for storage of exposed equipment, can be directly affected by the levels of activity induced and by the radioactive decay characteristics of the constituent elements. Since the activation cross sections and decay properties of these elements have been tabulated, the induced activity of different structural materials can be computed and analyzed.

We describe a computer program developed to catalog isotopic activities obtained for 19 elements following seven day and one year exposures to an intense flux of 14 MeV neutrons. These elements comprise the most prominent components of reactor-related structural materials. The results are presented as decay curves for each element, including the contributions from each isotope. This compilation makes possible a graphic analysis of the activation and decay properties for each element listed and permits comparison of anticipated levels of total activity for different elements. In addition, activation of representative alloys is simulated by combination of constituent element activities. Examples of this application are present in plots of radioactive decay curves generated for Inconel, Nitronic 33, and 304 steel.

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INTRODUCTION

The designer of future fusion reactors must give serious consideration to the activation properties of structural materials exposed to a substantial fast neutron flux. The principal fusion reaction

$$T + d \rightarrow n + \alpha + \text{Energy}$$

envisioned for power reactors, produces neutrons of approximately 14 MeV. While scattering of the high energy neutrons to lower energies is expected, a large fraction of neutrons impinging on the critical "first wall" structures will be within the 14 MeV range.

In order to categorize the fundamental activation and radioactive decay characteristics of possible structural materials, a computer code has been generated which simulates exposure of pertinent elements and alloys to a high flux of 14 MeV neutrons and traces the decay of the induced activity. Plots of specific activity versus time are compiled and describe the characteristic decay properties of the radioactive products that can be generated in a fusion reactor.

This memorandum has been prepared to provide a reference that can be used as a guide in the selection of materials for fusion reactor first wall structures. Since elements can be examined separately by the computer program, the activation problems associated with alloying constituents can be easily identified.

DESCRIPTION OF PROGRAM

PARAMETERS

We have simulated the continuous irradiation of 19 different elements by a 10^{15} n/(cm^2-sec) flux of 14 MeV neutrons for durations of seven days and one year. The flux level and irradiation

periods correspond to possible operating conditions for a fusion power reactor. The short period is selected to simulate the activity to be expected at maintenance periods during test operations while the long irradiation time is used to obtain the radioactivity levels anticipated after long term power generation.

The principal neutron-induced reactions, the 14 MeV cross sections, and the associated half lives for each of the related isotopes are presented in Table 1. Reactions are included which have cross sections greater than 0.03 mb and have product half lives between one minute and 10^6 years. Fractional abundances entered for each correspond to the naturally occurring weight ratios.

PROGRAM OPERATION

The program incorporates the options of analyzing an alloy composed of the listed elements or of selecting one or all of these elements for calculation. If one element is selected, the routine enters a request for the symbol of the element of interest and proceeds to search for the data array containing the parameters of the pertinent isotopes. If calculation of an alloy is required the number of elements and their respective symbols and weight fractions must be entered.

The calculation describing the isotopic induced activity contributing to the activation of an alloy is expressed as follows

$$A = \frac{W_a f N_o \rho}{A_o} (\sigma\Phi) \; [1 - \exp(-0.693 \; t_1/T_{\frac{1}{2}})][\exp(-0.693 \; t_2/T_{\frac{1}{2}})]$$

where

A = induced activity (dis/sec - cm^3)

ρ = density (gm/cm^3)

N_o = Avogadro number (6.02×10^{23})

W_a = weight fraction of element in alloy

f = fractional abundance (natural)

A_o = atomic weight

σ(mb) = cross section (units of millibarns)

Φ = flux [entered as 10^{15} n/(cm^2-sec) in the program]

$T_{\frac{1}{2}}$ = half life (hrs)

t_1 = irradiation period

t_2 = decay period

Disintegrations per sec/cm^3 are converted to Curies/cm^3 (1 Curie = 3.7×10^{10} dis/sec). To permit logarithmic representation a zero check is made, and if encountered, sets $A = 10^{-77}$.

At the end of the computation a disk file is automatically created for data storage (identified by elemental symbol or alloy name). A file for an element consists of a set of records containing the calculated activity of each reaction listed for it and one final record describing the total response for that element. A file created for an alloy consists of a record for each constituent element and a final record containing the data for the total response of the alloy.

Different irradiation time, alternate units of decay time representation, and additional elements may be easily introduced. Subsequent running of the program replaces the original file content with those data calculated with the new parameters. A listing of the program is presented in Appendix A.

TABLE 1 LIST OF REACTIONS

Reaction	No.	$T_{\frac{1}{2}}$ (hrs)	σ(14-15 MeV) (mb)	Frac Abun
$^{24}Mg(n,p)^{24}Na$	1	15.0	175	0.787
$^{27}Al(n,2n)^{26}Al$	1	6.5×10^{9}	4.5	1
$^{27}Al(n,p)^{27}Mg$	2	0.158	83	1
$^{27}Al(n,\alpha)^{24}Na$	3	15.0	115	1
$^{28}Si(n,p)^{28}Al$	1	0.039	200	0.922
$^{29}Si(n,p)^{29}Al$	2	0.110	225	0.047
$^{31}P(n,2n)^{30}P$	1	0.042	10	1
$^{31}P(n,p)^{31}Si$	2	2.62	110	1
$^{31}P(n,\alpha)^{28}Al$	3	0.039	115	1
$^{32}S(n,p)^{32}P$	1	343.2	225	0.95
$^{34}S(n,\alpha)^{31}Si$	2	2.62	130	0.0422
$^{36}S(n,2n)^{35}S$	3	2112	20	0.00014
$^{39}K(n,2n)^{38}K$	1	0.129	3.5	0.931
$^{39}K(n,p)^{39}Ar$	2	2.4×10^{6}	360	0.931
$^{39}K(n,\alpha)^{36}Cl$	3	2.7×10^{9}	108	0.931
$^{41}K(n,2n)^{40}K$	4	1.1×10^{13}	450	0.0688
$^{41}K(n,p)^{41}Ar$	5	1.83	78	0.0688
$^{41}K(n,\alpha)^{38}Cl$	6	0.622	28	0.0688
$^{46}Ti(n,2n)^{45}Ti$	1	3.09	33	0.0793
$^{46}Ti(n,p)^{46}Sc$	2	2016	285	0.0793
$^{47}Ti(n,p)^{47}Sc$	3	81.6	120	0.0728
$^{47}Ti(n,pn)^{46}Sc$	4	2016	50	0.0728
$^{48}Ti(n,p)^{48}Sc$	5	44	62	0.7394
$^{48}Ti(n,\alpha)^{45}Ca$	6	3960	47	0.7394
$^{48}Ti(n,pn)^{47}Sc$	7	81.6	12.4	0.7394
$^{49}Ti(n,p)^{49}Sc$	8	0.958	33	0.0551
$^{49}Ti(n,pn)^{48}Sc$	9	44	15	0.0551
$^{50}Ti(n,p)^{50}Sc$	10	0.030	22	0.0534
$^{50}Ti(n,\alpha)^{47}Ca$	11	112.8	8.6	0.0534
$^{50}V(n,2n)^{49}V$	1	7920	575	0.0024
$^{50}V(n,\alpha)^{47}Sc$	2	81.6	35	0.0024
$^{51}V(n,2n)^{50}V$	3	5.3×10^{19}	750	0.9976
$^{51}V(n,p)^{51}Ti$	4	0.097	35	0.9976
$^{51}V(n,\alpha)^{48}Sc$	5	44	25	0.9976
$^{51}V(n,\alpha n)^{47}Sc$	6	81.6	4.5	0.9976
$^{50}Cr(n,2n)^{49}Cr$	1	0.70	22	0.0431
$^{50}Cr(n,pn)^{49}V$	2	7920	200	0.0431
$^{52}Cr(n,2n)^{51}$	3	667.2	350	0.8376
$^{52}Cr(n,p)^{52}V$	4	0.063	112	0.8376

TABLE 1 (CONT) LIST OF REACTIONS

Reaction	No.	$T_{1/2}$ (hrs)	σ(14-15 MeV) (mb)	Frac Abun
$^{53}Cr(n,p)^{53}V$	5	0.033	40	0.0955
$^{54}Cr(n,\alpha)^{51}Ti$	6	0.097	16	0.0238
$^{55}Mn(n,2n)^{54}Mn$	1	7272	950	1
$^{55}Mn(n,p)^{55}Cr$	2	0.058	87	1
$^{55}Mn(n,\alpha)^{52}V$	3	0.063	34	1
$^{54}Fe(n,2n)^{53}Fe$	1	0.142	15.5	0.0582
$^{54}Fe(n,p)^{54}Mn$	2	7272	360	0.0582
$^{54}Fe(n,\alpha)^{51}Cr$	3	667.2	95	0.0582
$^{54}Fe(n,pn)^{53}Mn$	4	1.75×10^{10}	175	0.0582
$^{56}Fe(n,2n)^{55}Fe$	5	23652	400	0.9166
$^{56}Fe(n,p)^{56}Mn$	6	2.58	108	0.9166
$^{57}Fe(n,p)^{57}Mn$	7	0.028	95	0.0219
$^{57}Fe(n,pn)^{56}Mn$	8	2.58	13	0.0219
$^{58}Fe(n,\alpha)^{55}Cr$	9	0.058	14	0.0033
$^{58}Fe(n,p)^{58}Mn$	10	0.018	20	0.0033
$^{59}Co(n,2n)^{58}Co$	1	1704	265	1
$^{59}Co(n,2n^*)^{58m}Co$	2	9.0	400	1
$^{59}Co(n,p)^{59}Fe$	3	1080	80	1
$^{59}Co(n,\alpha)^{56}Mn$	4	2.58	28	1
$^{58}Ni(n,2n)^{57}Ni$	1	36	33	0.6788
$^{58}Ni(n,p)^{58}Co$	2	1704	400	0.6788
$^{58}Ni(n,p^*)^{58m}Co$	3	9.0	360	0.6788
$^{58}Ni(n,\alpha)^{57}Co$	4	6528	550	0.6788
$^{58}Ni(n,\alpha)^{55}Fe$	5	23652	150	0.6788
$^{58}Ni(n,pn)^{57}Co$	6	6408	550	0.6788
$^{60}Ni(n,2n)^{59}Ni$	7	7.0×10^{8}	300	0.2623
$^{60}Ni(n,p)^{60}Co$	8	46078	120	0.2623
$^{60}Ni(n,p^*)^{60m}Co$	9	0.175	12	0.2623
$^{61}Ni(n,p)^{61}Co$	10	1.65	96	0.0119
$^{61}Ni(n,pn)^{60}Co$	11	46078	3.7	0.0119
$^{61}Ni(n,pn^*)^{60m}Co$	12	0.175	3.7	0.0119
$^{62}Ni(n,p)^{62}Co$	13	0.232	22	0.0366
$^{62}Ni(n,p^*)^{62m}Co$	14	0.027	22	0.0366
$^{62}Ni(n,\alpha)^{59}Fe$	15	1080	20	0.0366
$^{62}Ni(n,pn)^{61}Co$	16	1.65	4.3	0.0366
$^{64}Ni(n,2n)^{63}Ni$	17	8.1×10^{5}	1030	0.0108
$^{64}Ni(n,p)^{64}Co$	18	0.130	3	0.0108

TABLE 1 (CONT) LIST OF REACTIONS

Reaction	No.	$T_{1/2}$ (hrs)	σ(14-15 MeV) (mb)	Frac Abun
$^{64}Ni(n,p^*)^{64m}Co$	19	0.033	3	0.0108
$^{64}Ni(n,\alpha)^{61}Fe$	20	0.10	1.5	0.0108
$^{63}Cu(n,2n)^{62}Cu$	1	0.165	550	0.6909
$^{63}Cu(n,p)^{63}Ni$	2	8.1×10^5	119	0.6909
$^{63}Cu(n,\alpha)^{60}Co$	3	4.6×10^4	35	0.6909
$^{63}Cu(n,\alpha^*)^{60m}Cu$	4	0.175	23	0.6909
$^{63}Cu(n,He^3)^{61}Co$	5	1.65	2	0.6909
$^{65}Cu(n,2n)^{64}Cu$	6	12.9	950	0.6909
$^{65}Cu(n,p)^{65}Ni$	7	2.56	21	0.3091
$^{65}Cu(n,\alpha)^{62}Co$	8	0.232	12.5	0.3091
$^{65}Cu(n,\alpha^*)^{62m}Co$	9	0.027	1.9	0.3091
$^{65}Cu(n,\alpha n)^{61}Co$	10	1.65	2.8	0.3091
$^{64}Zn(n,2n)^{63}Zn$	1	0.63	175	0.4889
$^{64}Zn(n,p)^{64}Cu$	2	12.9	180	0.4889
$^{66}Zn(n,2n)^{65}Zn$	3	5880	600	0.2781
$^{66}Zn(n,p)^{66}Cu$	4	0.085	77	0.2781
$^{66}Zn(n,\alpha)^{63}Ni$	5	8.1×10^5	50	0.2781
$^{67}Zn(n,p)^{67}Cu$	6	61	56	0.0411
$^{67}Zn(n,pn)^{66}Cu$	7	0.085	20	0.0411
$^{68}Zn(n,\alpha)^{65}Ni$	8	2.56	18	0.1857
$^{68}Zn(n,pn)^{67}Cu$	9	59	2.5	0.1857
$^{70}Zn(n,2n)^{69}Zn$	10	0.92	310	0.0062
$^{70}Zn(n,2n^*)^{69m}Zn$	11	14	920	0.0062
$^{70}Zn(n,\alpha)^{67}Ni$	12	0.014	11	0.0062
$^{92}Mo(n,2n)^{91}Mo$	1	0.258	160	0.1584
$^{92}Mo(n,2n^*)^{91m}Mo$	2	0.018	16	0.1584
$^{92}Mo(n,p)^{92}Nb$	3	242.4	65	0.1584
$^{92}Mo(n,\alpha)^{89}Zn$	4	78.4	19	0.1584
$^{92}Mo(n,\alpha^*)^{89m}Zn$	5	0.07	6.5	0.1584
$^{92}Mo(n,pn^*)^{91m}Nb$	6	1488	44	0.1584
$^{94}Mo(n,2n)^{93}Mo$	7	8.8×10^6	570	0.0904
$^{94}Mo(n,2n^*)^{93m}Mo$	8	6.9	570	0.0904
$^{94}Mo(n,p)^{94}Nb$	9	1.75×10^8	6	0.0904
$^{94}Mo(n,p^*)^{94m}Nb$	10	0.105	6	0.0904
$^{95}Mo(n,p)^{95}Nb$	11	840	26	0.1572
$^{95}Mo(n,p^*)^{95m}Nb$	12	90	26	0.1572
$^{95}Mo(n,pn)^{94}Nb$	13	1.75×10^8	6.5	0.1572

TABLE 1 (CONT) LIST OF RACTIONS

Reaction	No.	$T_{\frac{1}{2}}$ (hrs)	σ(14-15 MeV) (mb)	Frac Abun
$^{95}Mo(n,pn^*)^{94m}Nb$	14	0.105	6.5	0.1572
$^{96}Mo(n,p)^{96}Nb$	15	23	27	0.1653
$^{96}Mo(n,\alpha)^{93}Zn$	16	1.3×10^{10}	13.5	0.1653
$^{96}Mo(n,pn)^{95}Nb$	17	840	5	0.1653
$^{96}Mo(n,pn^*)^{95m}Nb$	18	90	1.8	0.1653
$^{97}Mo(n,p)^{97}Nb$	19	1.2	78	0.0946
$^{97}Mo(n,p^*)^{97m}Nb$	20	0.017	7.7	0.0946
$^{97}Mo(n,pn)^{96}Nb$	21	23	2.4	0.0946
$^{98}Mo(n,p)^{98}Nb$	22	0.858	14	0.2378
$^{98}Mo(n,pn)^{97}Nb$	23	1.2	0.8	0.2378
$^{98}Mo(n,pn^*)^{97m}Nb$	24	0.017	0.25	0.2378
$^{100}Mo(n,2n)^{99}Mo$	25	67	2250	0.0963
$^{100}Mo(n,\alpha)^{97}Zn$	26	17	13.5	0.0963
$^{107}Ag(n,2n)^{106}Ag$	1	0.4	700	0.5182
$^{107}Ag(n,2n^*)^{106m}Ag$	2	201.6	530	0.5182
$^{107}Ag(n,\alpha n^*)^{103m}Rh$	3	0.95	2	0.5182
$^{109}Ag(n,2n)^{108}Ag$	4	0.04	950	0.4818
$^{109}Ag(n,2n^*)^{108m}Ag$	5	43800	28	0.4818
$^{109}Ag(n,p)^{109}Pd$	6	13.5	7.2	0.4818
$^{109}Ag(n,p^*)^{109}Pd$	7	0.078	7.2	0.4818
$^{109}Ag(n,\alpha^*)^{106m}Rh$	8	2.167	25	0.4818
$^{109}Ag(n,\alpha n)^{105}Rh$	9	35.9	0.55	0.4818
$^{93}Nb(n,2n^*)^{92m}Nb$	1	242.4	430	1
$^{93}Nb(n,p)^{93}Zn$	2	1.3E10	44	1
$^{93}Nb(n,\alpha)^{90}Y$	3	64.2	9.5	1
$^{93}Nb(n,\alpha^*)^{90m}Y$	4	3.2	5.5	1
$^{93}Nb(n,n^*)^{93m}Nb$	5	32412	330	1
$^{180}Ta(n,2n)^{179}Ta$	1	14400	2250	0.000123
$^{180}Ta(n,n^*)^{180m}Ta$	2	8.1	1000	0.000123
$^{181}Ta(n,2n^*)^{180m}Ta$	3	8.1	1100	0.99988
$^{181}Ta(n,3n)^{179}Ta$	4	14400	2	0.99988
$^{181}Ta(n,p)^{181}HF$	5	1020	2.6	0.99988
$^{181}Ta(n,\alpha)^{178}Lu$	6	0.5	1.2	0.99988
$^{181}Ta(n,\alpha^*)^{178m}Lu$	7	0.33	0.03	0.99988
$^{13}C(n,\alpha)^{10}Be$	1	2.4E10	130	0.0111
$^{10}B(n,t)^{8}Be$	1	1.08E5	100	0.196
$^{11}B(n,t)^{9}Be$	2	1.08E5	17.2	0.804

USE OF CURVES

The plots of radioactive decay for the seven day and one year operations are given in Appendices B and C, respectively. The data in this report are presented in a log-log display, with the abscissa in units of years from 10^{-6} to 10^{3} and the ordinate in Curies/cm^3, specific activity, encompassing values from 10^{-3} to 10^{4}. The use of many orders of magnitude for both axes permits the compact display of the total responses as well as the distinct contribution of individual reaction to this activity for different decay times.

The actual data points plotted correspond to abscissa values E+n and $\sqrt{10}$ E+n where E+n is 10^{+n} $(-6 \leq n \leq 3)$. The lines connecting these points are meant to guide the eye and to display the over-all trend of the decay curve. A listing relating 10^{+n} years to more conventional time units (i.e., 10^{-6} years = 31.6 sec) is presented in Table 2.

TABLE 2 CONVERSION TO STANDARD TIME UNITS

Years	Convenient Time Units
1E3	1000 yrs
1E2	100 yrs
1E1	10 yrs
1E0	1 yr
1E-1	36.5 days
1E-2	3.65 days
1E-3	8.76 hrs
1E-4	52.6 min
1E-5	5.26 min
1E-6	31.6 sec

For the sake of brevity, the data plotted here are derived from an arbitrarily chosen set of parameters: 10^{15} n/(cm^2-sec), 14 MeV neutrons, seven day and one year irradiations, natural abundances. The value of specific activity, however, may be easily adjusted to reflect a different flux level or an assumed weight fraction by application of the appropriate multiplication factor. For example, the activity obtained with the stipulated flux of 10^{15} n/(cm^2-sec) may be varied to reflect that expected at 10^{14} by multiplying by 1/10. By the use of appropriate factors, the plotted data can easily be generalized to provide information about a variety of physical conditions without resorting to the generation of individual plots for each parameter change.

An example of the application of the program option for analysis of alloys is presented in Figs. 1 and 2. The first figure displays the total activity obtained for 304 steel following irradiation by a 10^{13} n/(cm^2-sec) flux of 14 MeV neutrons for a 1000 sec period. The weight percent of the constituent elements in the alloy and their respective activity contributions are indicated in this figure. Figure 2 demonstrates another study in which the activation characteristics of different alloys are to be compared. The activation conditions for this comparison are the same as those used to generate the curves in Fig. 1. For the sake of clarity, the constituent contributions for each alloy are not plotted.

CONCLUSION

The set of curves tabulated in this report permits a compact graphic compilation of activation and radioactive decay characteristics for 19 elements of importance in fusion reactor structural

design. In addition, the program incorporates the option to examine alloys composed of the listed elements. Requirements for evaluation of activation effects based upon more detailed flux and spectral distributions can be accommodated as they arise. In this regard, the present report serves not only as a useful reference but also as a basis for future simulation.

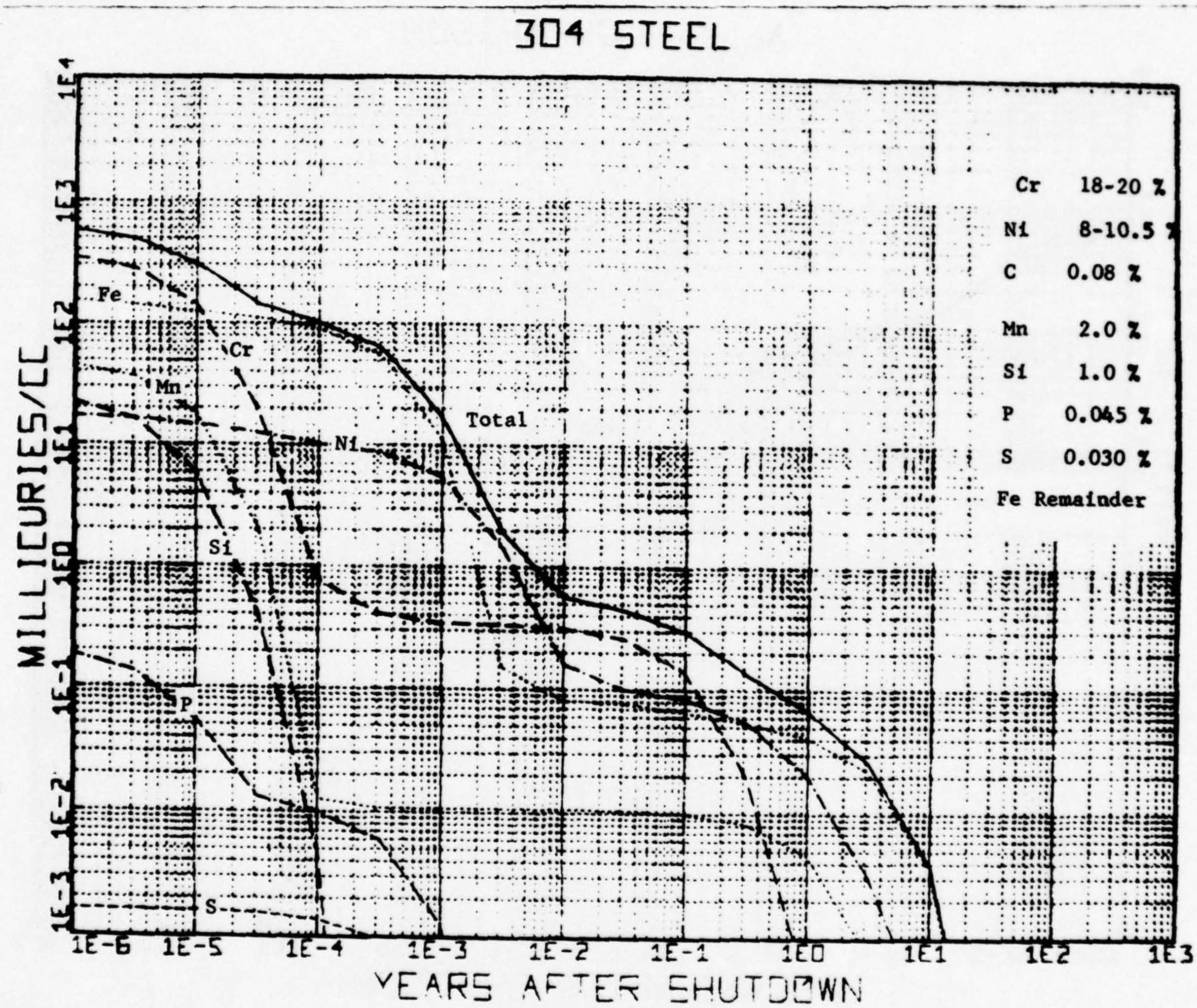

Fig. 1 Radioactive Decay of 304 Steel and Constituents Following 1000 Sec Irradiation by 10^{13} n/(cm^2-sec) Flux of 14 MeV Neutrons

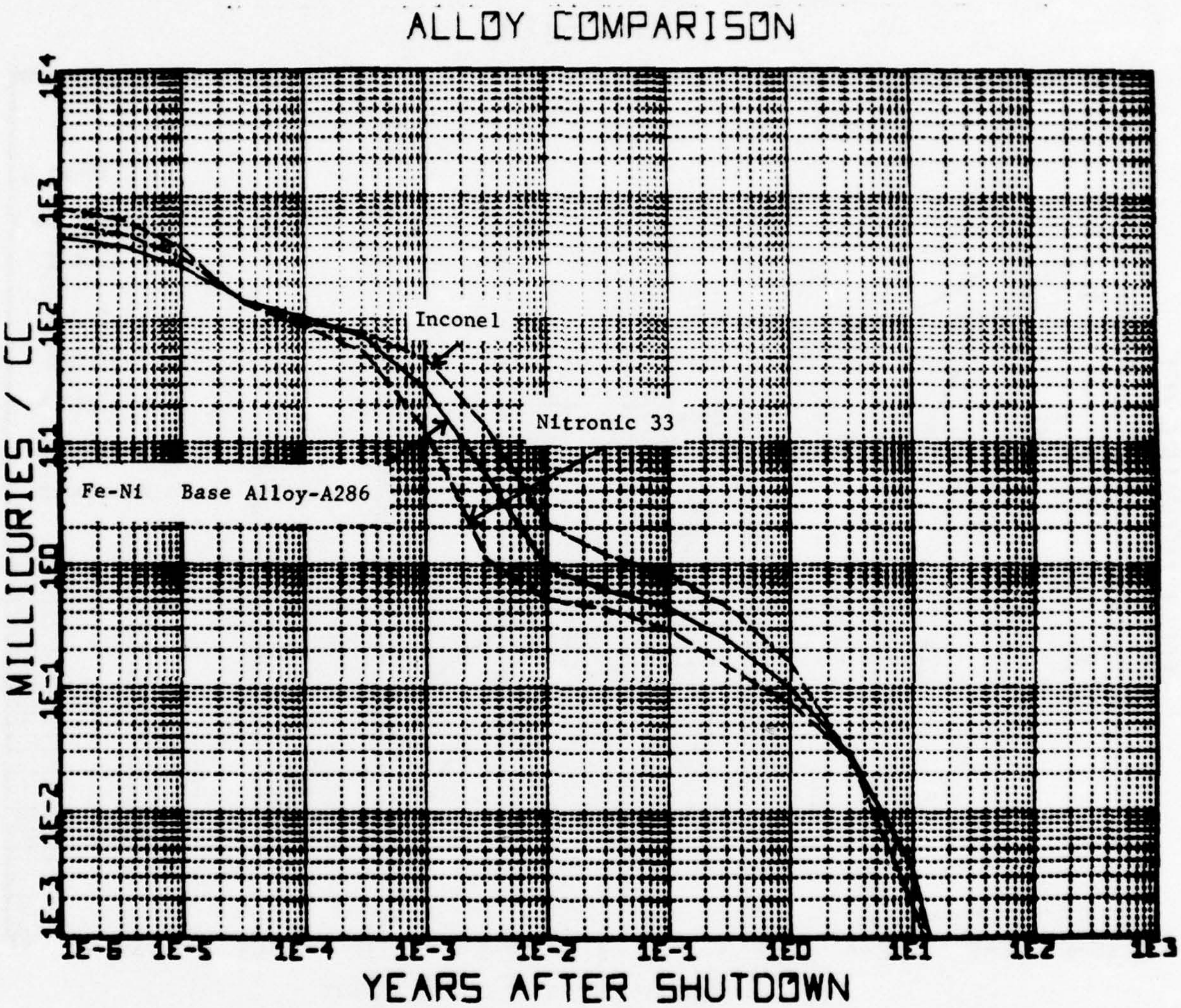

Fig. 2 Comparison of Radioactive Decay Curves for Inconel, Nitronic 33, and Fe-Ni Alloy (A286), Following 1000 Sec Irradiation by 10^{13} n/(cm^2-sec) Flux of 14 MeV Neutrons

APPENDIX A

LISTING OF PROGRAM ACTALOY

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ACTALOY
 10 REM COMPUTE SPECIFIC ACTIVITY
 20 REM ELEMENTS NB,TA,C,B
 30 REM ELEMENTS MG,AL,SI,P,S,K,TI,V,CR,MN,FE,CO,NI,CU,ZN,AG,MO
 40 FILES *,*
 50 DIM G$[2],M$[2],Y$[1],N$[1],S$[8]
 60 REM WGT  FRAC  IS SET TO 1 IN NEXT LINE
 70 W1=1
 80 DIM A[50],L1[50],D[50,25],R[1,50],B[1,25],T1[25]
 90 DIM W[20],E[50,25],F[1,50],H[1,25]
100 REM FLUX =10^13 N/CM^3/SEC
110 F1=1E13
120 N0=6.02E23
130 INPUT "DO ALL ELEMENTS ? (YES OR NO)  ",Y$
140 IF Y$="Y" THEN 260
150 INPUT "DOING AN ALLOY? ",N$
160 IF N$="N" THEN 250
170 J=0
180 INPUT "ALLOY NAME (FILE) AND # OF ELEMENTS ",S$,M
190 REDIM E[M,25],F[1,M]
200 CREATE Q1,S$,M+1,106
210 ASSIGN S$,2,R0
220 J=J+1
230 INPUT "ELEMENT SYMBOL AND WGT  FRAC. IN ALLOY ",M$,W1
240 GOTO 260
250 INPUT "ENTER SYMBOL OF REQUIRED ELEMENT ",M$
260 RESTORE
270 IF TYP(0)=3 THEN 850
280 IF TYP(0)=2 THEN 310
290 READ D1
300 GOTO 270
310 READ G$,N,R1,A1
320 IF Y$="Y" THEN 350
330 IF M$=G$ THEN 350
340 GOTO 270
350 CREATE Q1,G$,N+1,106
360 ASSIGN G$,1,R0
370 REDIM D[N,25],A[N],L1[N],R[1,N]
380 REM HRS V=1,DAYS V=24,WKS V=168,MO.(30) V=720,YRS(365) V=8760
390 V=8760
400 REM T = DURATION OF OPERATION (HRS.)
410 T=1000/3600
420 FOR I=1 TO N
430   READ H1,S1,F2
440   L1[I]=.693/H1
450   A[I]=((R1*N0*W1*F2)/A1)*S1*F1*(1E-27)*(1-EXP(-L1[I]*T))
460   C=0
470   FOR K=1 TO 25
480     T1[K]=V*(10**((-13+K)/2))
490     REM MILLICURIES/CC
500     C=A[I]*EXP(-L1[I]*T1[K])
510     C=C/(3.7E7)
520     IF C>0 THEN 540
530     C=1E-77
540     PRINT #1,10**((-13+K)/2),C
550     D[I,K]=C
560   NEXT K
570   PRINT #1,END
580   READ #1,REC(1)+1
590 NEXT I
600 MAT R=CON
610 MAT B=R*D
620 FOR K=1 TO 25
630   PRINT #1,10**((-13+K)/2),B[1,K]
640 NEXT K
650 PRINT #1,END
660 IF Y$="Y" THEN 830
670 IF N$="N" THEN 830
680 FOR K=1 TO 25
690   PRINT #2,10**((-13+K)/2),B[1,K]
700   E[J,K]=B[1,K]
710 NEXT K
720 PRINT #2,END
730 READ #2,REC(2)+1
740 IF J<M THEN 220
750 MAT F=CON
760 MAT H=F*E
770 FOR K=1 TO 25
780   PRINT #2,10**((-13+K)/2),H[1,K]
790 NEXT K
800 PRINT #2,END
810 PRINT S$,H[1,1]
820 STOP
830 PRINT G$,B[1,1]
840 IF Y$="Y" THEN 270
850 STOP
>
```

```
ACTALOY
 860 REM SYMBOL.# OF REACTIONS.(GM/CC).AT WGT
 870 DATA 'MG'.1.1 74.24 312
 880 REM T1/2(HRS).MBARNS.FR ABUN
 890 DATA 15.175. 787
 900 DATA 'AL'.3.2 702.26 9815
 910 DATA 6 48E9.4 5.1. 158.83.1.15.115.1
 920 DATA 'SI'.2.2 33.28 086
 930 DATA .039.200. 922. 11.225. 047
 940 DATA 'P'.3.2 7.123 895
 950 DATA  042.10.1.2 62.110.1. 039.115.1
 960 DATA 'S'.3.2 07.32 064
 970 DATA 343 2.225. 95.2 62.130. 0422.2112.20. 00014
 980 DATA 'K'.6. 89.39 102
 990 DATA .129.3 5. 931.2 36E6.360. 931.2 27E9.108. 931
1000 DATA 1 1E13.450. 0688.1 83.78. 0688. 622.28. 0688
1010 DATA 'TI'.11.4 5.47 9
1020 DATA 3 09.33. 0793.2016.285. 0793.81 6.120. 0728
1030 DATA 2016.50. 0728.44.62. 7394.3960.47. 7394
1040 DATA 81 6.12 4. 7394. 958.33. 0551.44.15. 0551
1050 DATA .03.22. 0534.112 8.8 6. 0534
1060 DATA 'V'.6.5 96.50 942
1070 DATA 7920.575. 0024.81 6.35. 0024.5 3E19.750. 9976
1080 DATA .097.35. 9976.44.25. 9976.81.6.4.5. 9976
1090 DATA 'CR'.6.7 2.51 996
1100 DATA .7.22. 0432.7920.200. 0431.667.2.350. 8376
1110 DATA .063.112. 8376. 033.40. 0955. 097.16. 0238
1120 DATA 'MN'.3.7 2.54 933
1130 DATA 7272.550.1. 053.87.1. 063.34.1
1140 DATA 'FE'.10.7 86.55 847
1150 DATA .142.15 5. 0582.7272.360. 0582.087.2.95. 0582
1160 DATA 1 75E10.175. 0582.23652.400. 9166.2 58.108. 9166
1170 DATA  028.95. 0219.2 58.13. 0219. 058.14. 0033. 018.20. 0033
1180 DATA 'CO'.4.0 0.58 933
1190 DATA 1704.265.1.9.400.1.1080.80.1.2.58.28.1
1200 DATA 'NI'.20.8 9.58.71
1210 DATA 36.33. 6788.1704.400. 6788.9.360. 6788
1220 DATA 6528.550. 6788.23652.150. 6788.6408.550. 6788
1230 DATA 7E8.300. 2623.46078.120. 2623. 175.12. 2623
1240 DATA 1 65.96. 0119.46078.3 7. 0119. 175.3 7. 0119
1250 DATA .232.22. 0366. 027.22. 0366.10 .20. 0366
1260 DATA 1 65.4 3. 0366.806000.1030. 0108. 13.3. 0108
1270 DATA .033.3. 0108. 1.1 5. 0108
1280 DATA 'CU'.10.8 92.63 546
1290 DATA  165.550. 6909.806000.119. 6909.46000.35. 6909
1300 DATA .175.23. 6909.1 65.2. 6909.12.9.950. 6909
1310 DATA 2 56.21. 3091. 232.12 5. 3091. 027.1.9. 3091.1.65.2.8. 3091
1320 DATA 'ZN'.12.7 14.65 37
1330 DATA .63.175. 4889.12 9.180. 4889.5880.600. 2781
1340 DATA .085.77. 2781.806000.50. 2781.61.56. 0411
1350 DATA .085.20. 0411.2 56.18. 1857.59.2.5. 1857
1360 DATA .92.310. 0062.14.920. 0062. 014.11. 0062
1370 DATA 'AG'.9.10 5.107 868
1380 DATA  4.700. 5182.201 6.530. 5182. 95.2. 5182
1390 DATA .04.950. 4818.43800.28. 4818.13 5.7.2. 4818
1400 DATA .078.7.2. 4818.2.167.25. 4818.35 9. 55. 4818
1410 DATA 'MO'.26.10 2.95 94
1420 DATA  258.160. 1584. 018.18. 1584.242 4.65. 1584
1430 DATA 78 4.19. 1584. 07.6.5. 1584.1483.44. 1584
1440 DATA 8 70E6.570. 0904.6 9.570. 0904.1 75E8.6. 0904
1450 DATA  10 .6. 0904.840.26. 1572.90.26. 1572
1460 DATA 1 7 .6 5. 1572. 105.6 5. 1572.23.27. 1653
1470 DATA 1 31E10.13 5. 1653.840.5. 1653.90.1 8. 1653
1480 DATA 1 2.78. 0946. 017.7 7. 0946.23.2 4. 0946
1490 DATA  858.14. 2378.1 2. 8. 2378. 017. 25. 2378
1500 DATA 67.2250. 0963.17.13 5. 0963
1510 DATA 'NB'.5.8 57.92 906
1520 DATA 242 4.430.1.1 3E10.44.1.64 2.9 5.1
1530 DATA 3 2.5 5.1.32412.330.1
1540 DATA 'TA'.7.16 6.180 948
1550 DATA 14400.2250. 000123.8.1.1000. 000123.8.1.1100. 99988
1560 DATA 14400.2. 99988.1020.2 6. 99988
1570 DATA .5.1 2. 99988. 33. 03. 99988
1580 DATA 'C'.1.2 1.12 0112
1590 DATA 2.4E10.130. 0111
1600 DATA 'B'.2.2 35.10 811
1610 DATA 108000.100. 196.108000.17.2. 804
1620 END
>
```

APPENDIX B

DECAY CURVES - SEVEN DAY ACTIVATION

This appendix contains the radioactive decay curves (Figs. B-1 through B-19) generated by the computer code ACTALOY for 19 elements: Mg, Al, Si, P, S, K, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ag, Mo, Nb, and Ta.

The data simulates the activity derived from a seven day continuous irradiation by a 10^{15} n/(cm^2-sec) flux of 14 MeV neutrons.

The number adjacent to a curve refers to the reaction listed for the element in Table 1. The solid curve labeled "Total" represents the expected activity for an element obtained from the sum of its individually numbered isotope reactions.

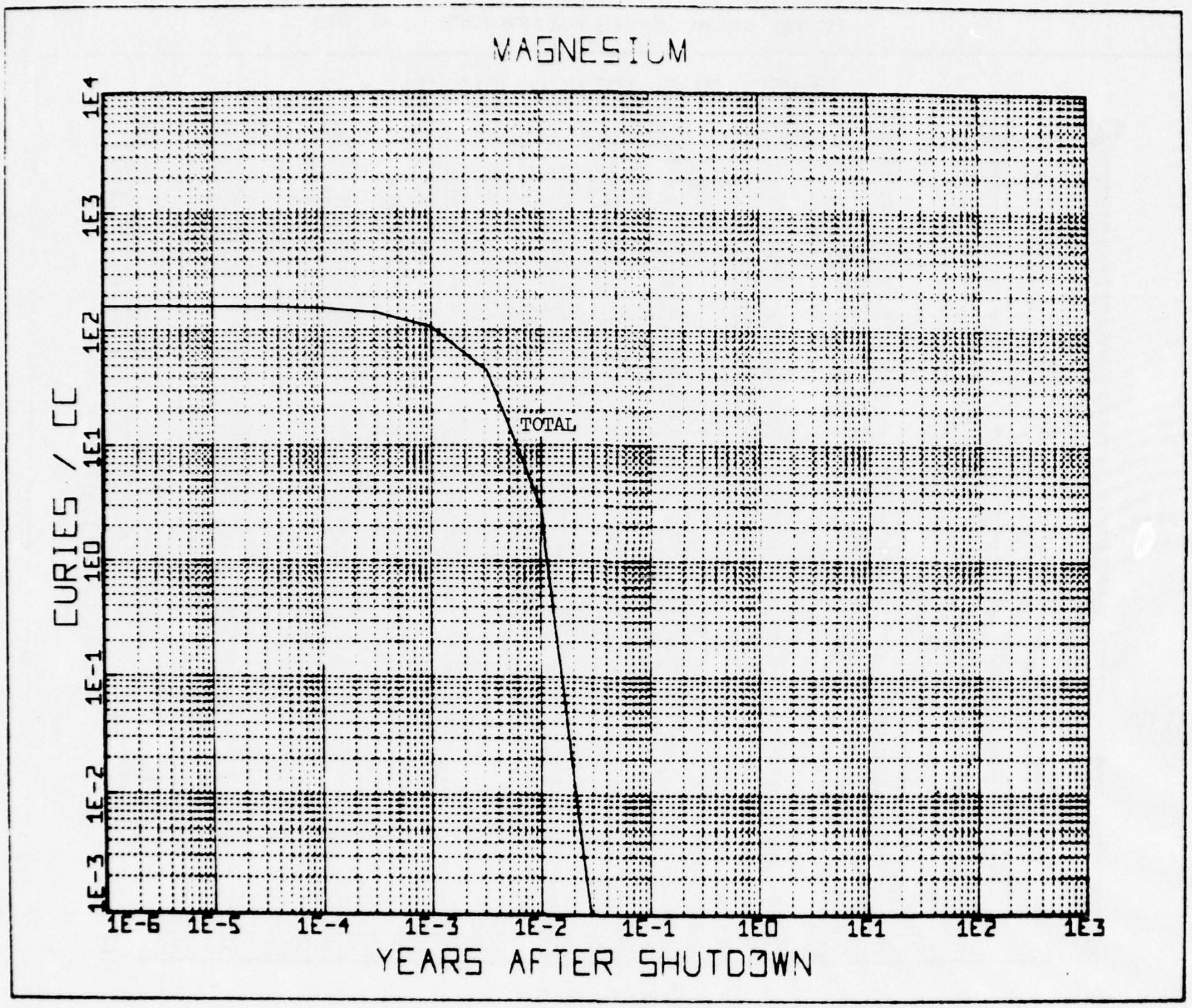

Fig. B-1 Radioactive Decay Curves for Mg

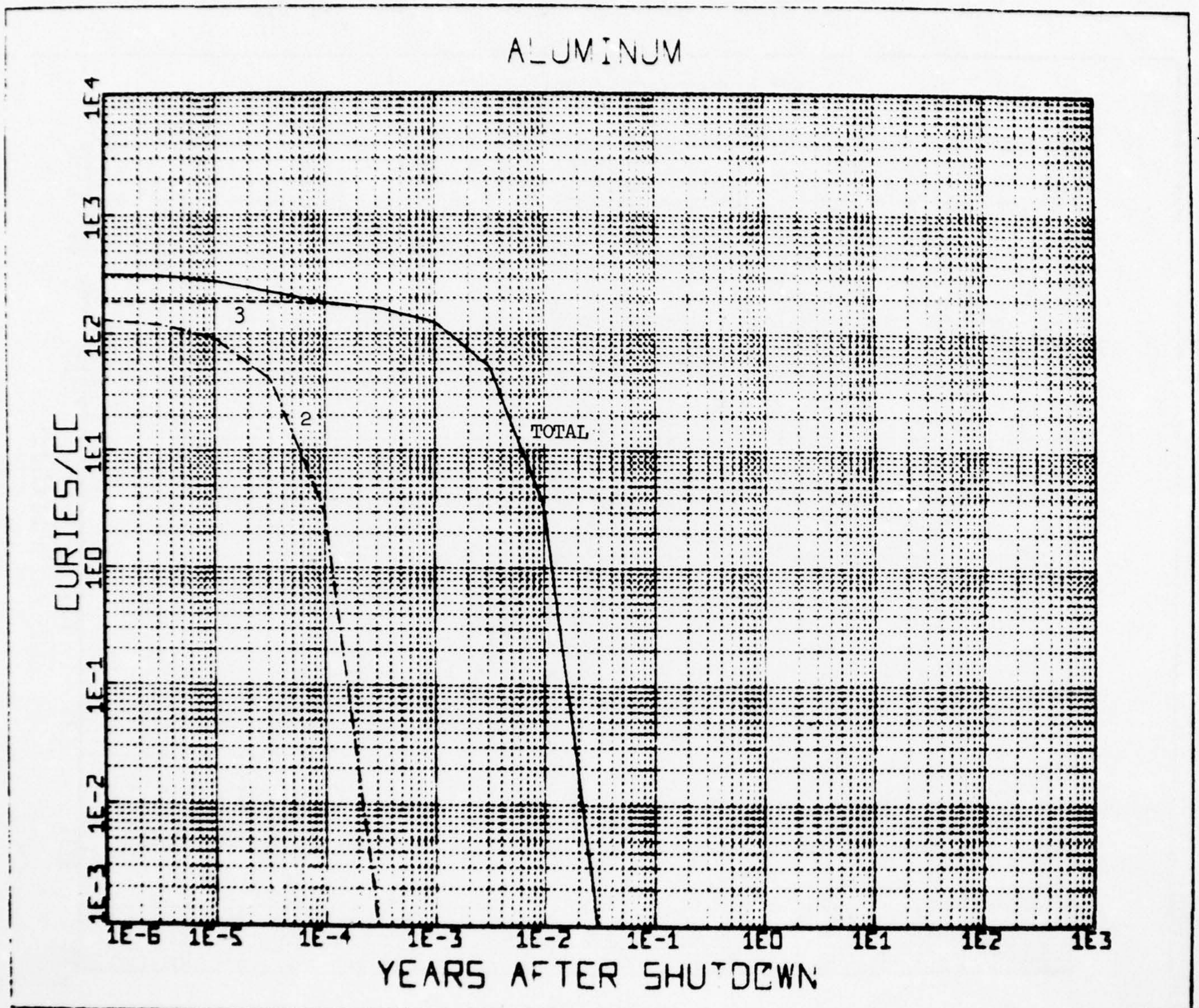

Fig. B-2 Radioactive Decay Curves for Al

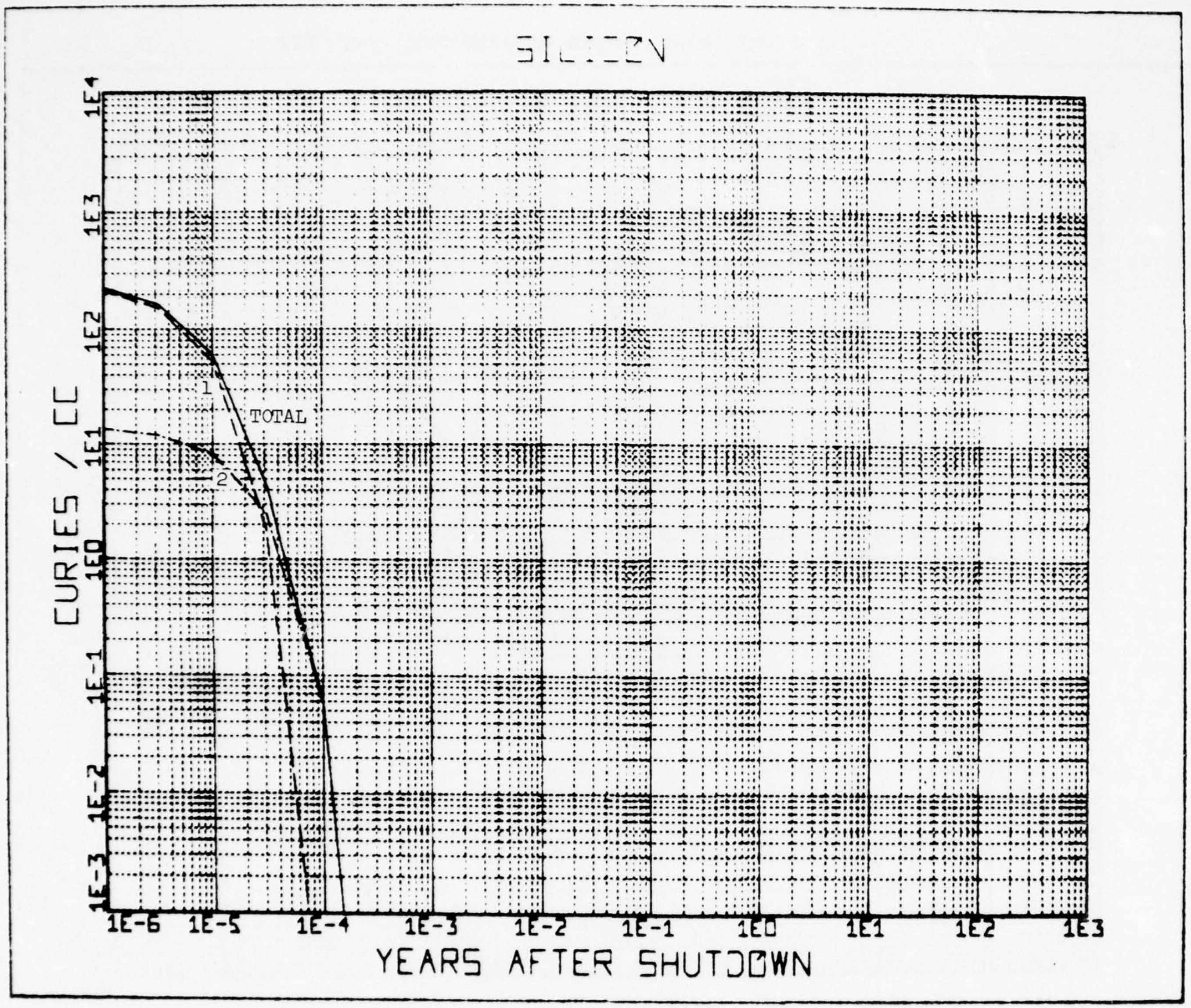

Fig. B-3 Radioactive Decay Curves for Si

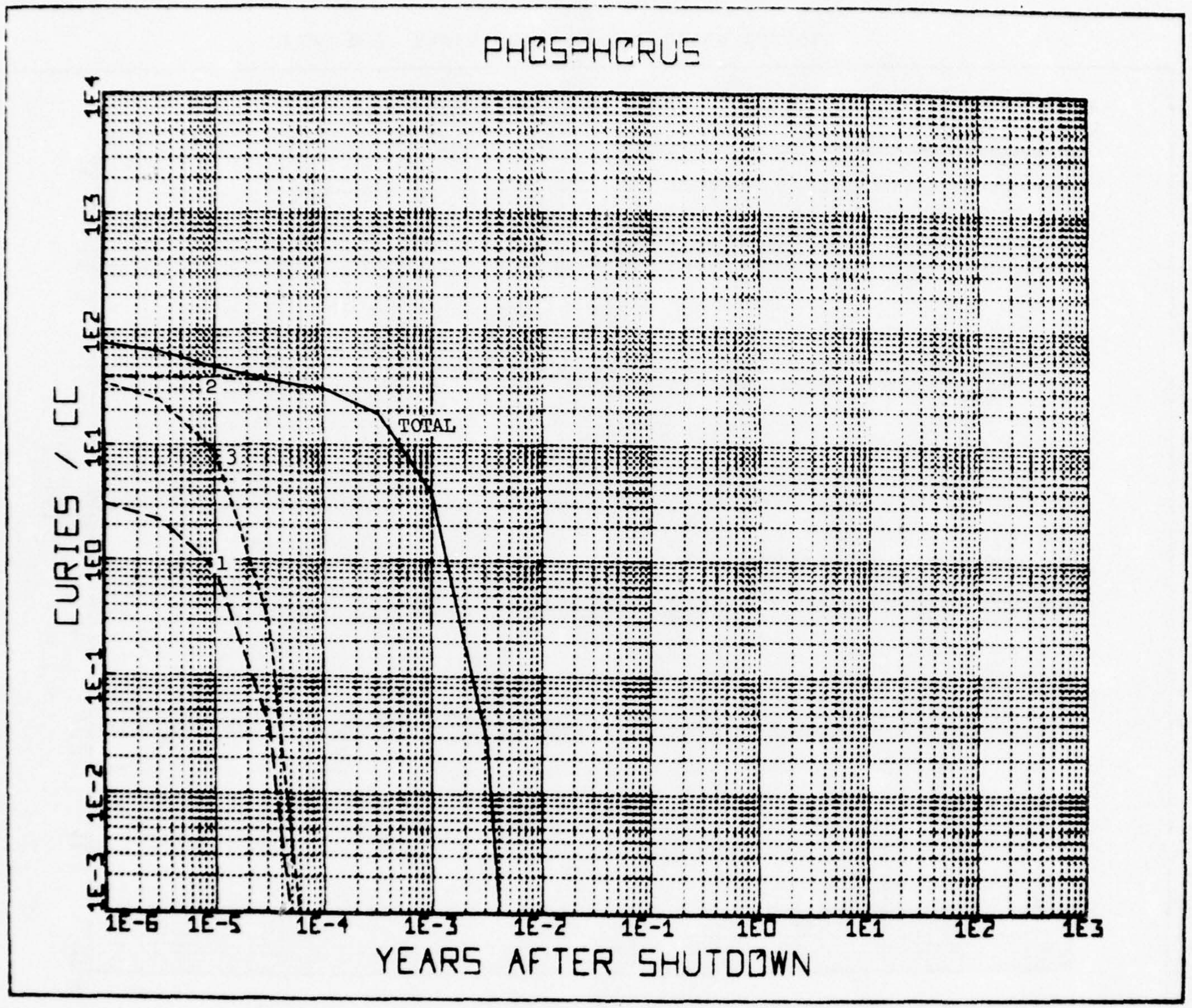

Fig. B-4 Radioactive Decay Curves for P

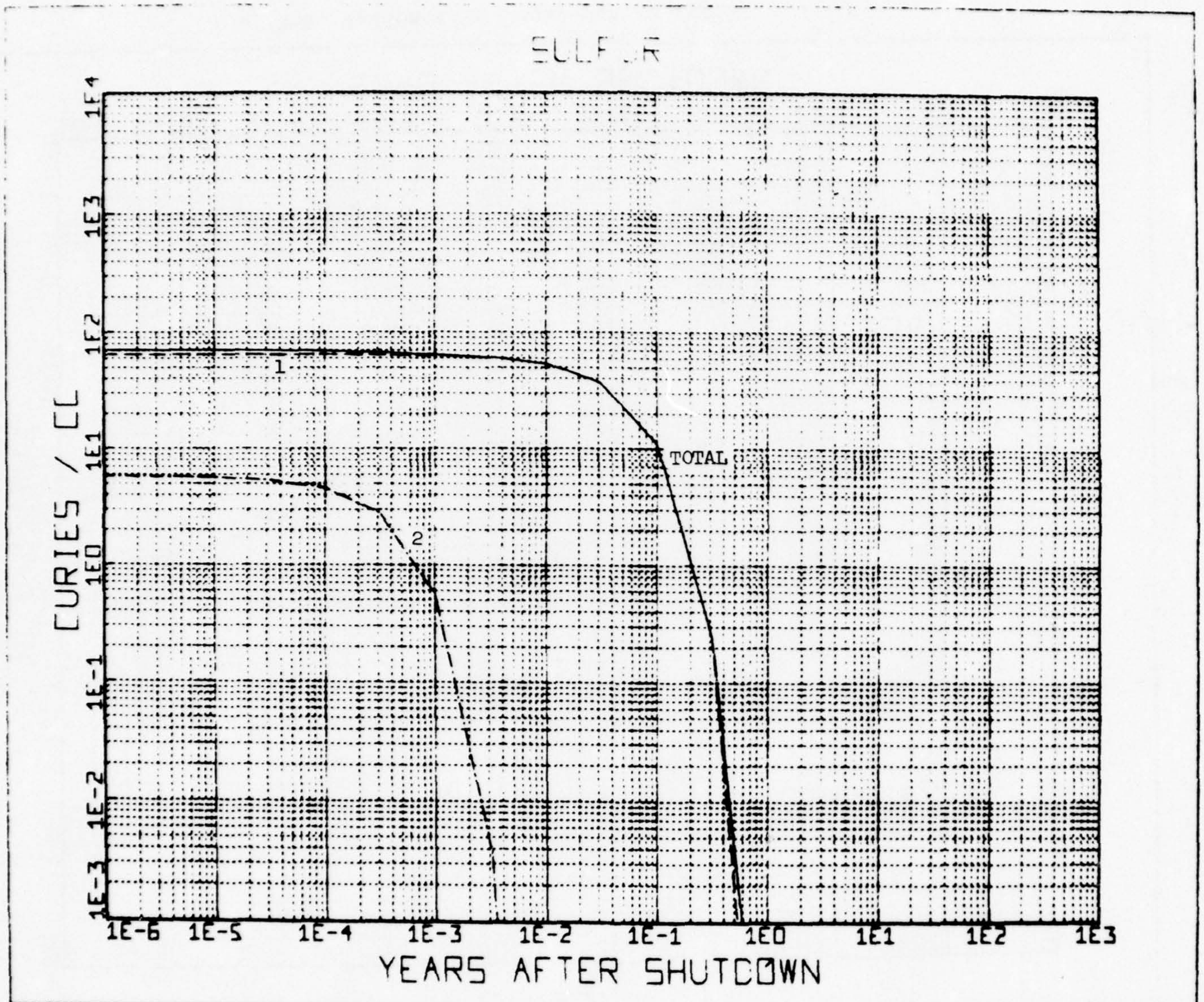

Fig. B-5 Radioactive Decay Curves for S

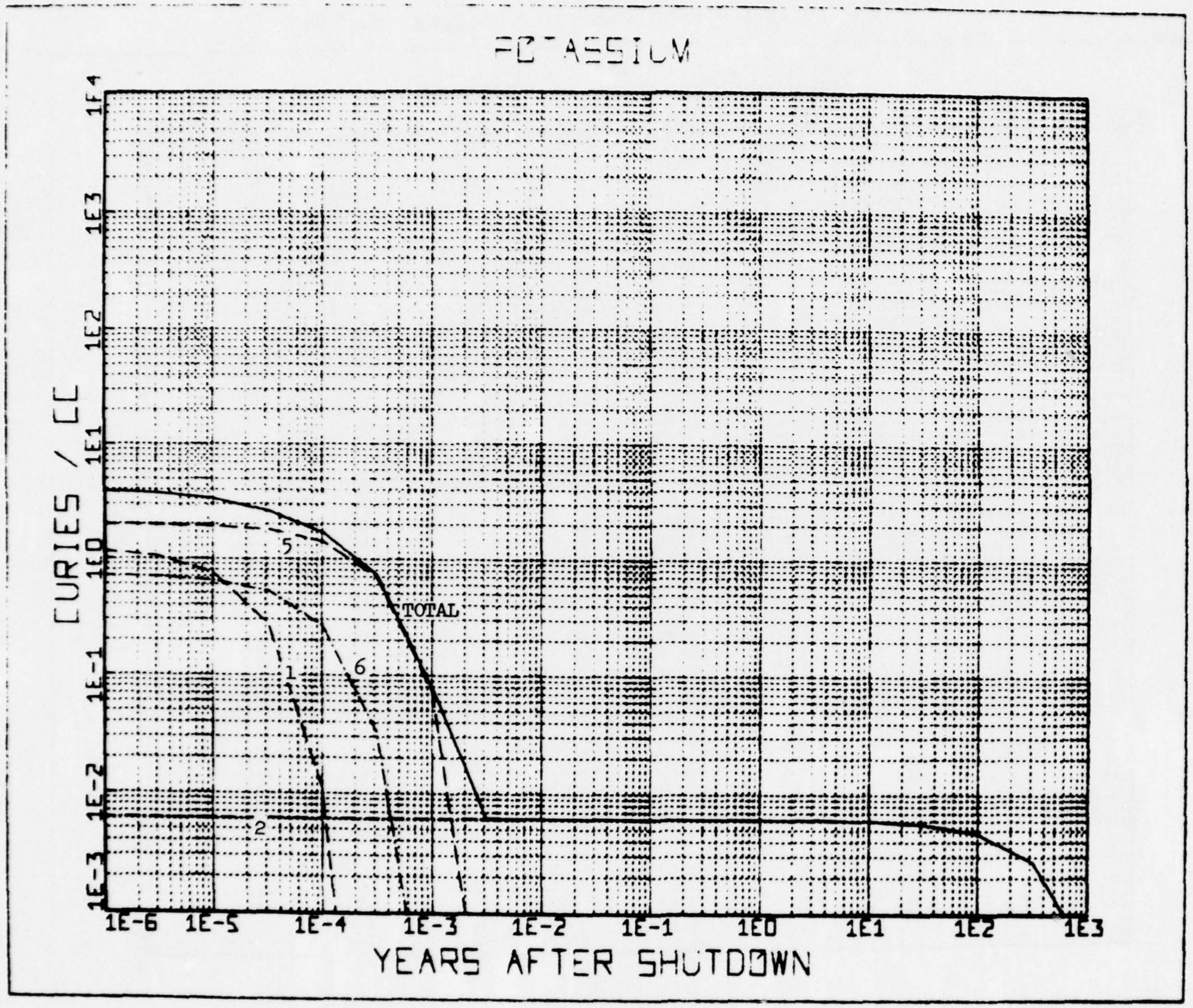

Fig. B-6 Radioactive Decay Curves for K

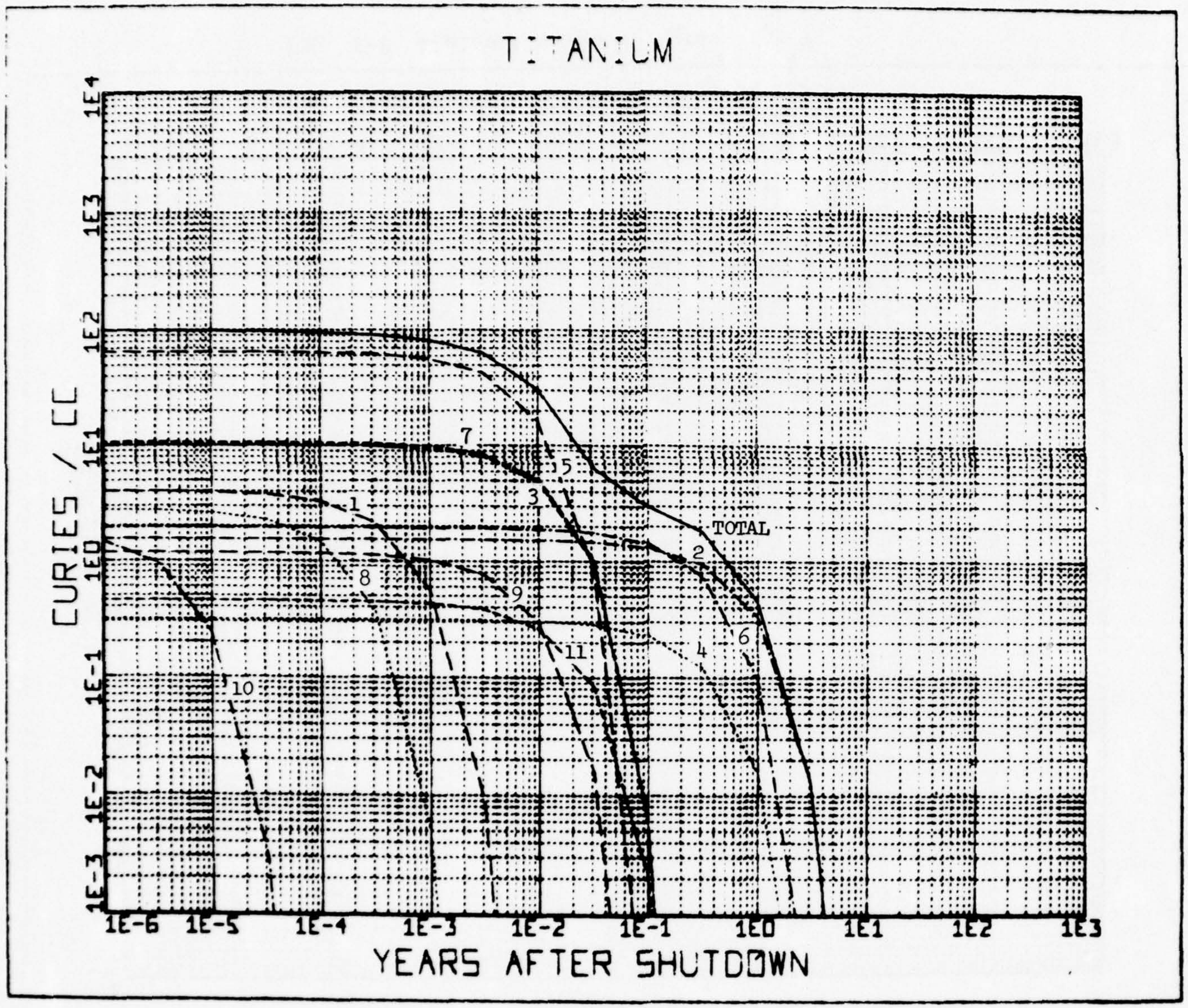

Fig. B-7 Radioactive Decay Curves for Ti

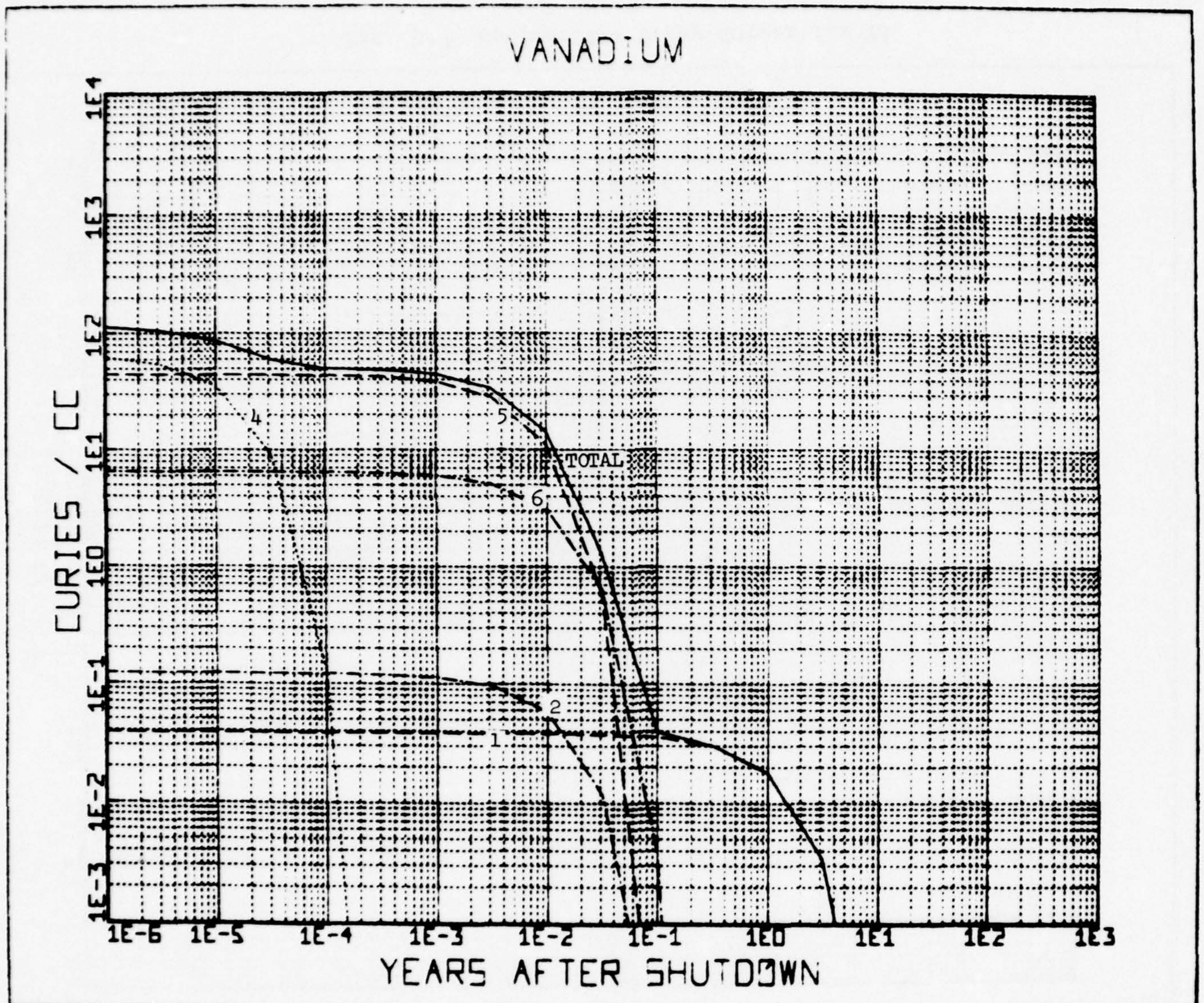

Fig. B-8 Radioactive Decay Curves for V

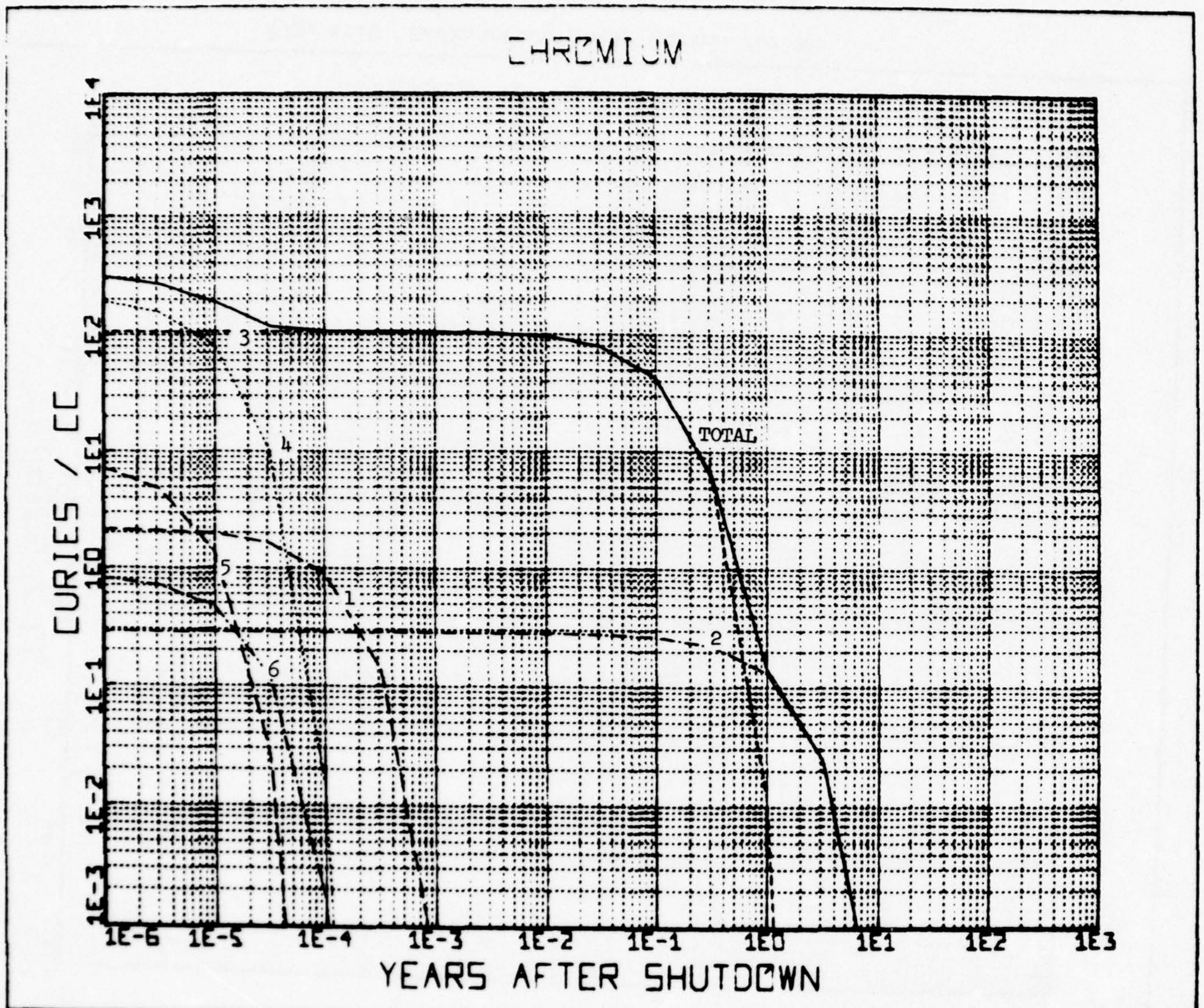

Fig. B-9 Radioactive Decay Curves for Cr

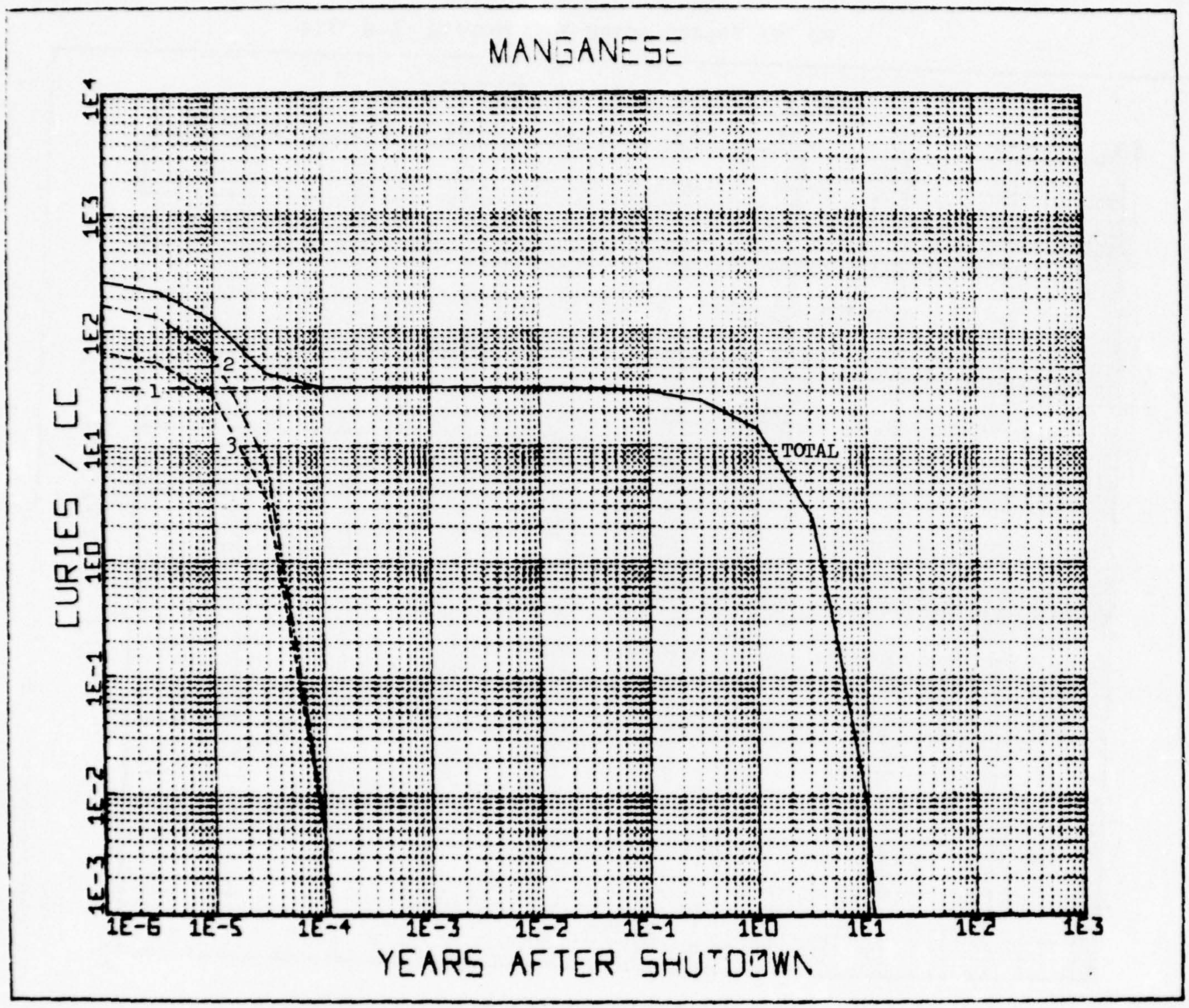

Fig. B-10 Radioactive Decay Curves for Mn

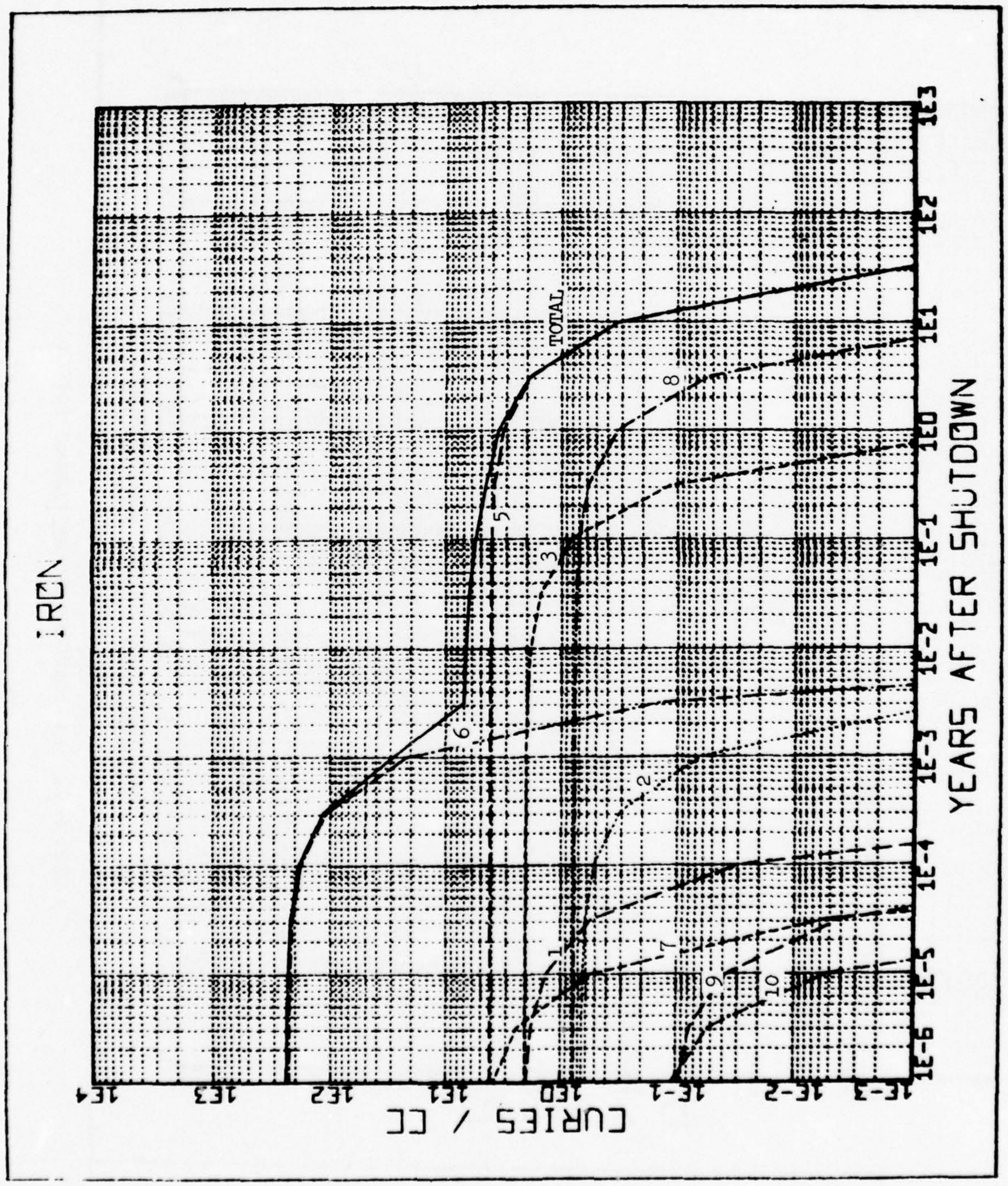

Fig. B-11 Radioactive Decay Curves for Fe

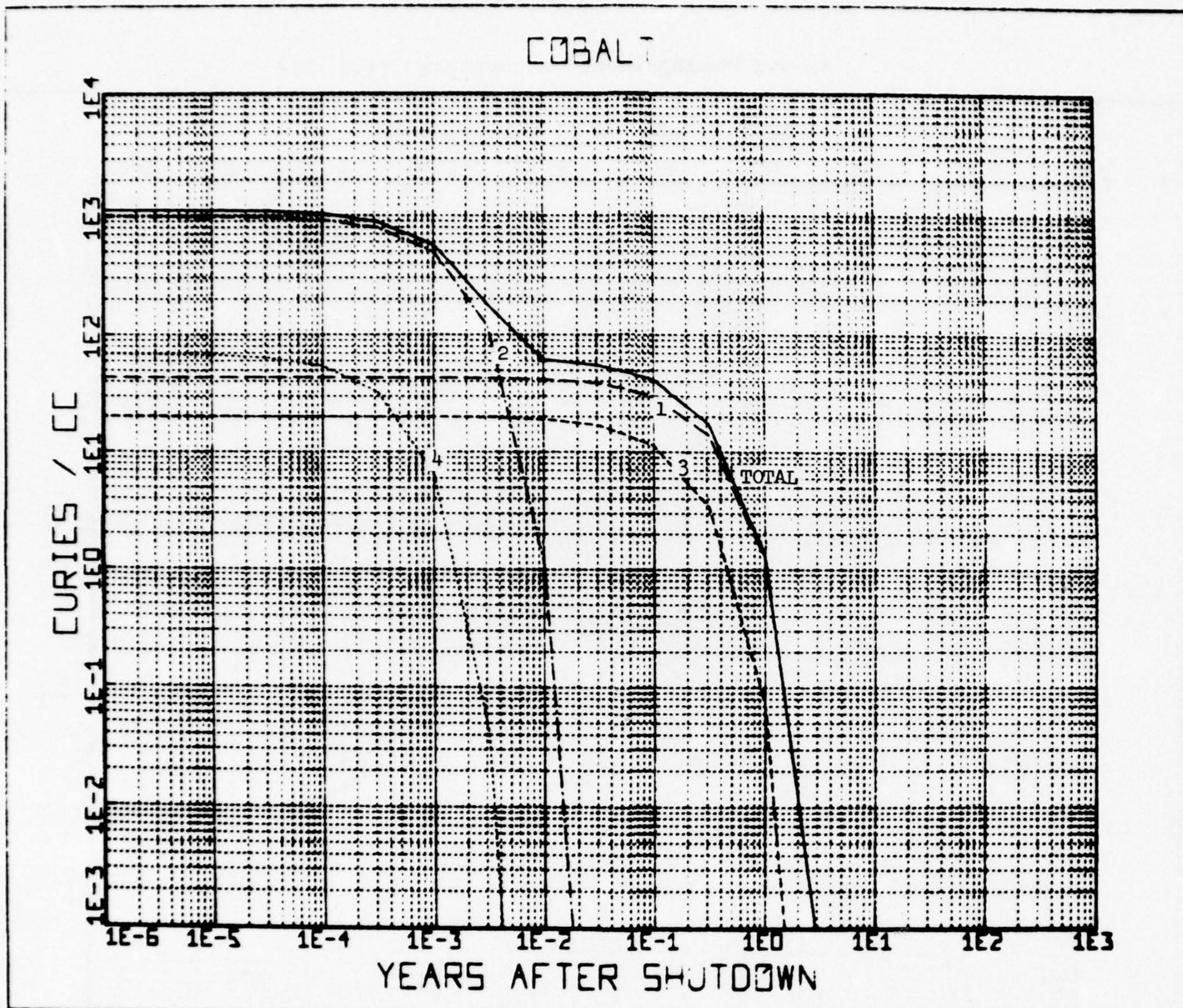

Fig. B-12 Radioactive Decay Curves for Co

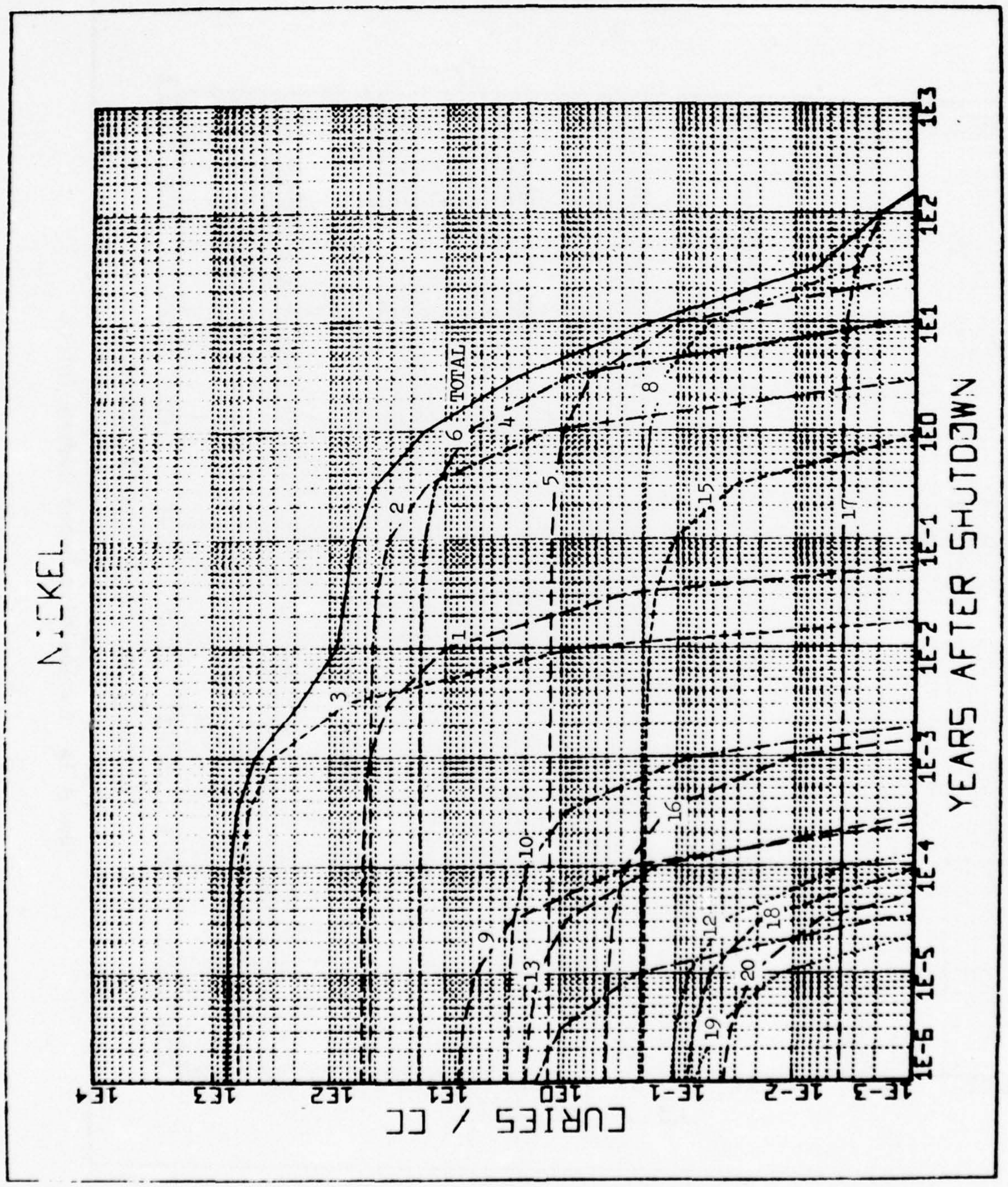

Fig. B-13 Radioactive Decay Curves for Ni

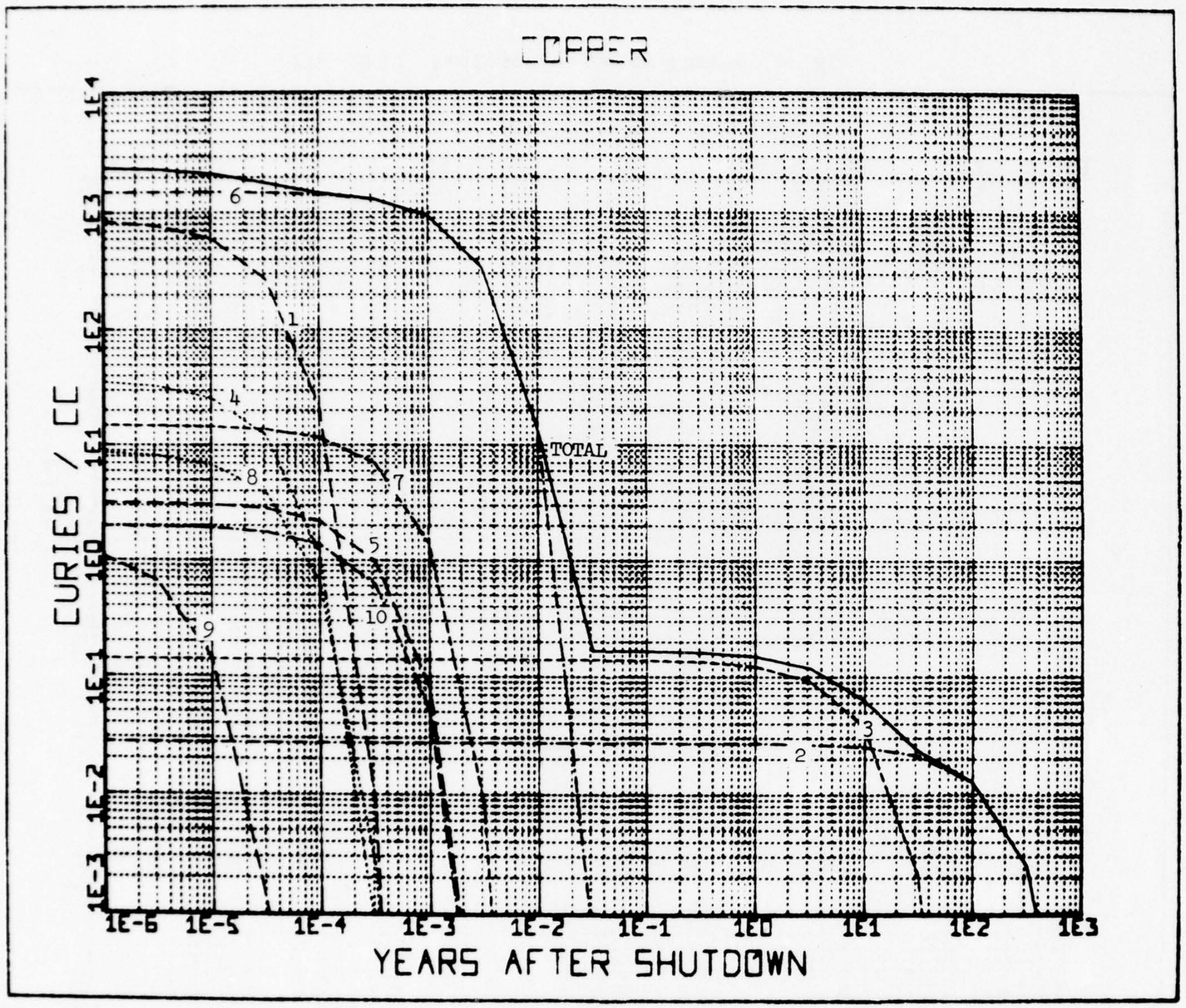

Fig. B-14 Radioactive Decay Curves for Cu

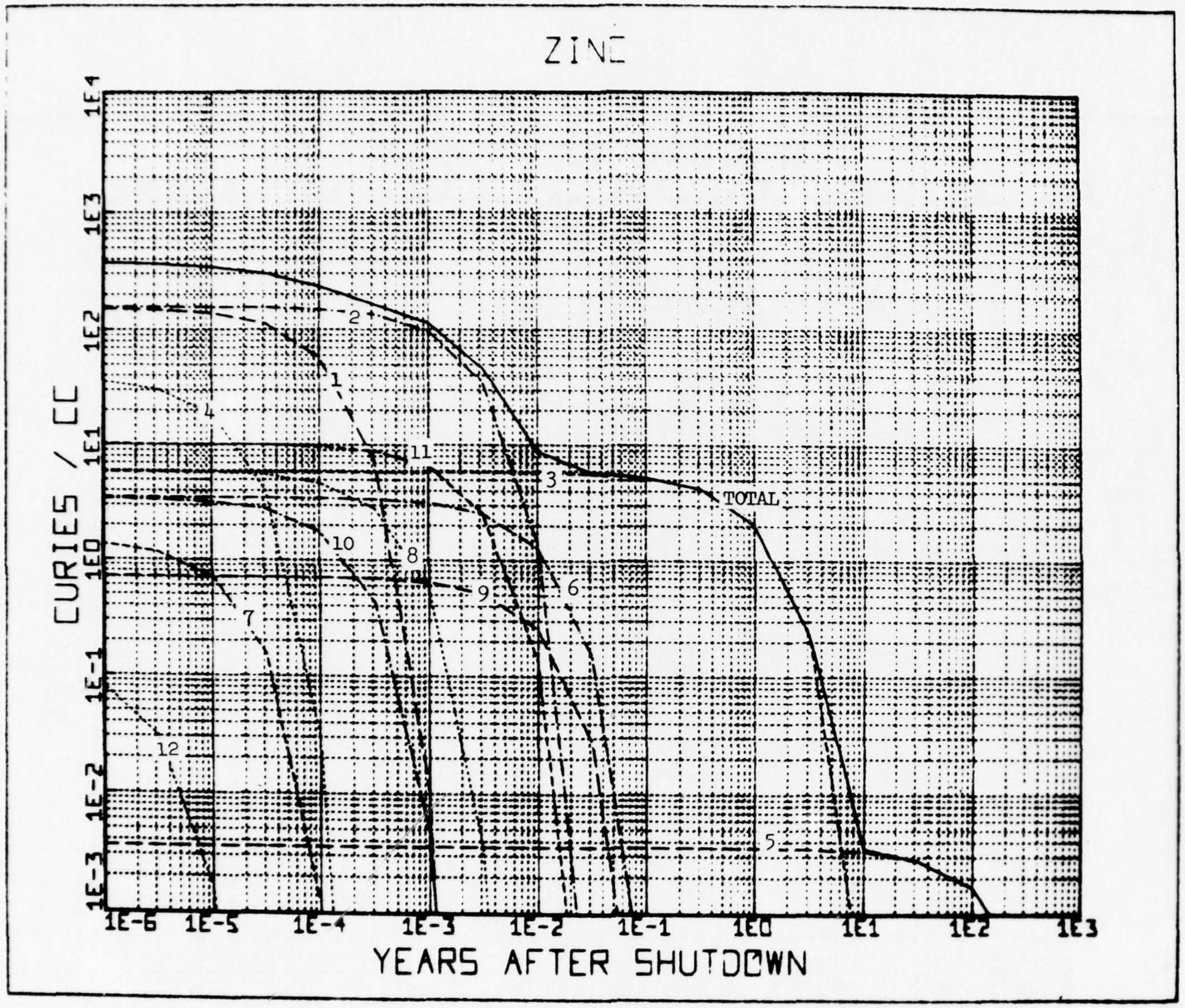

Fig. B-15 Radioactive Decay Curves for Zn

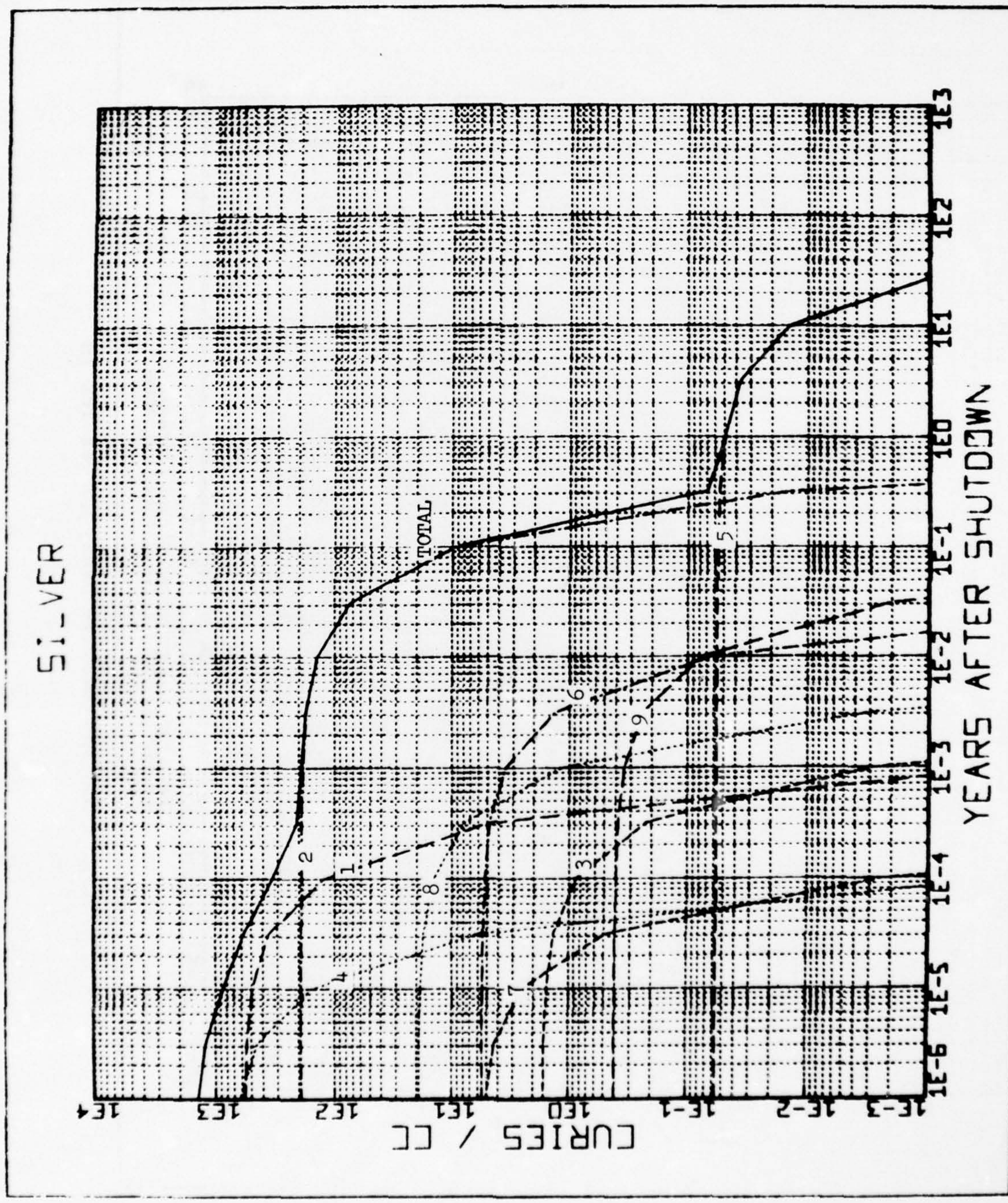

Fig. B-16 Radioactive Decay Curves for Ag

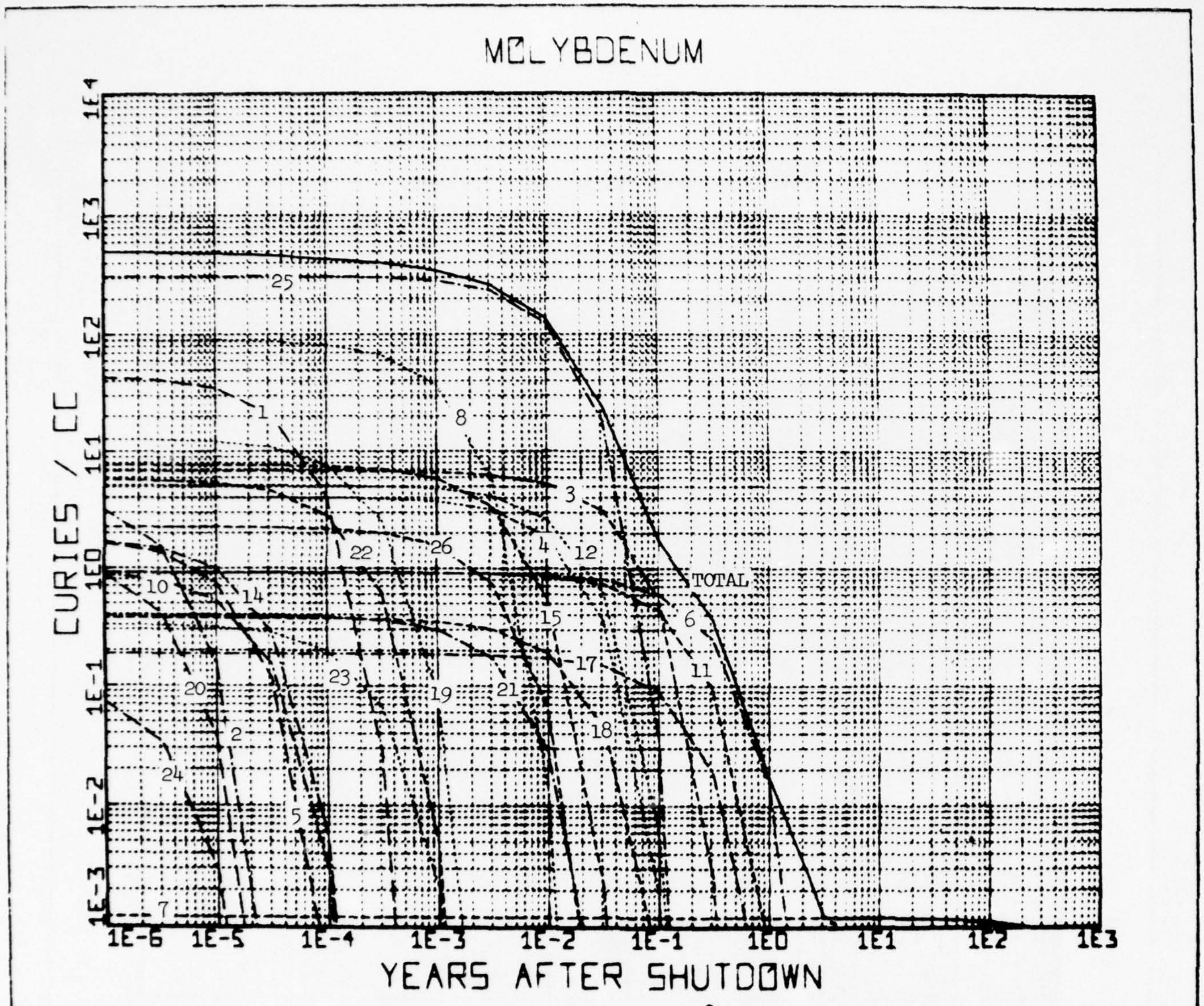

Fig. B-17 Radioactive Decay Curves for Mo

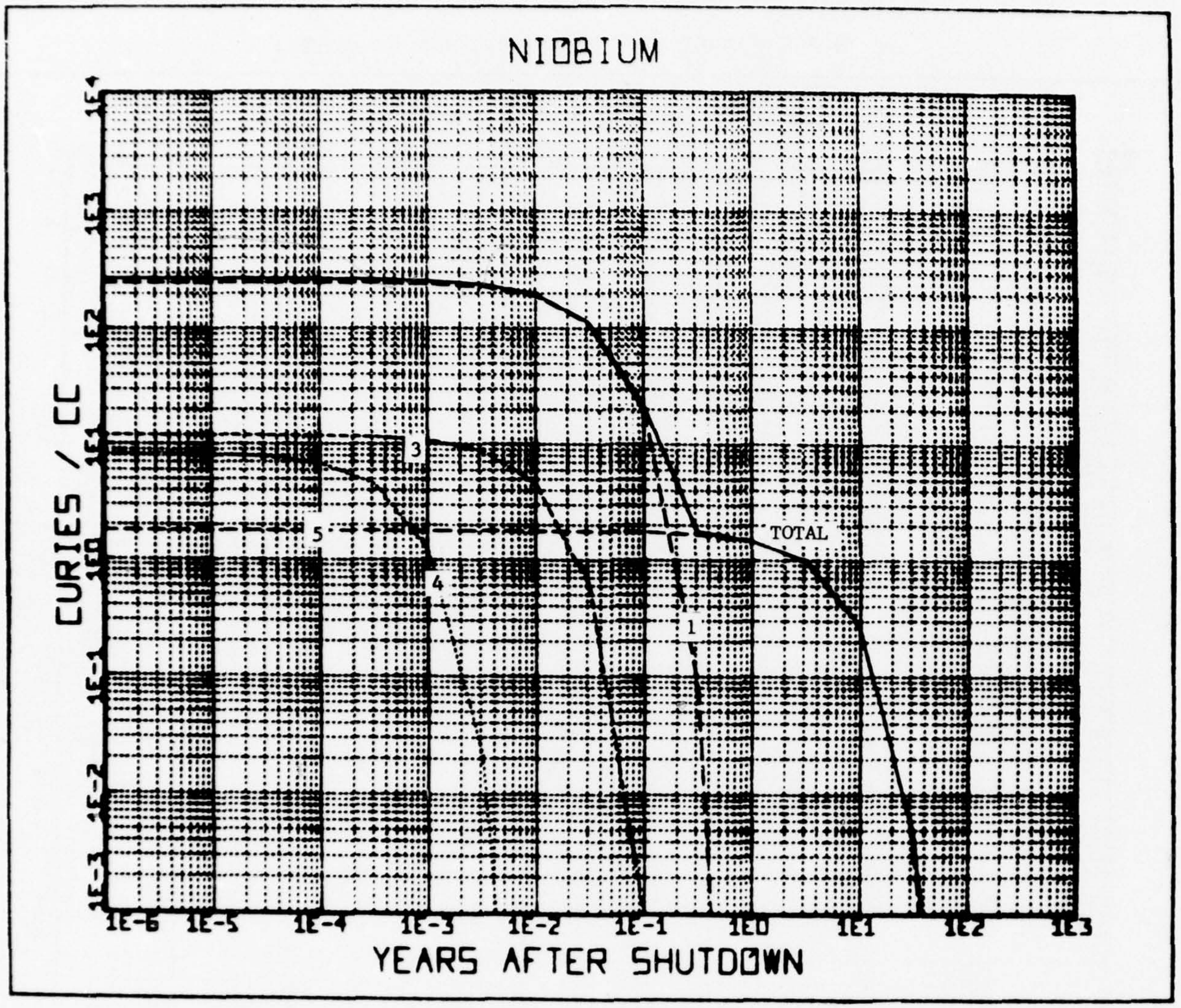

Fig. B-18 Radioactive Decay Curves for Nb

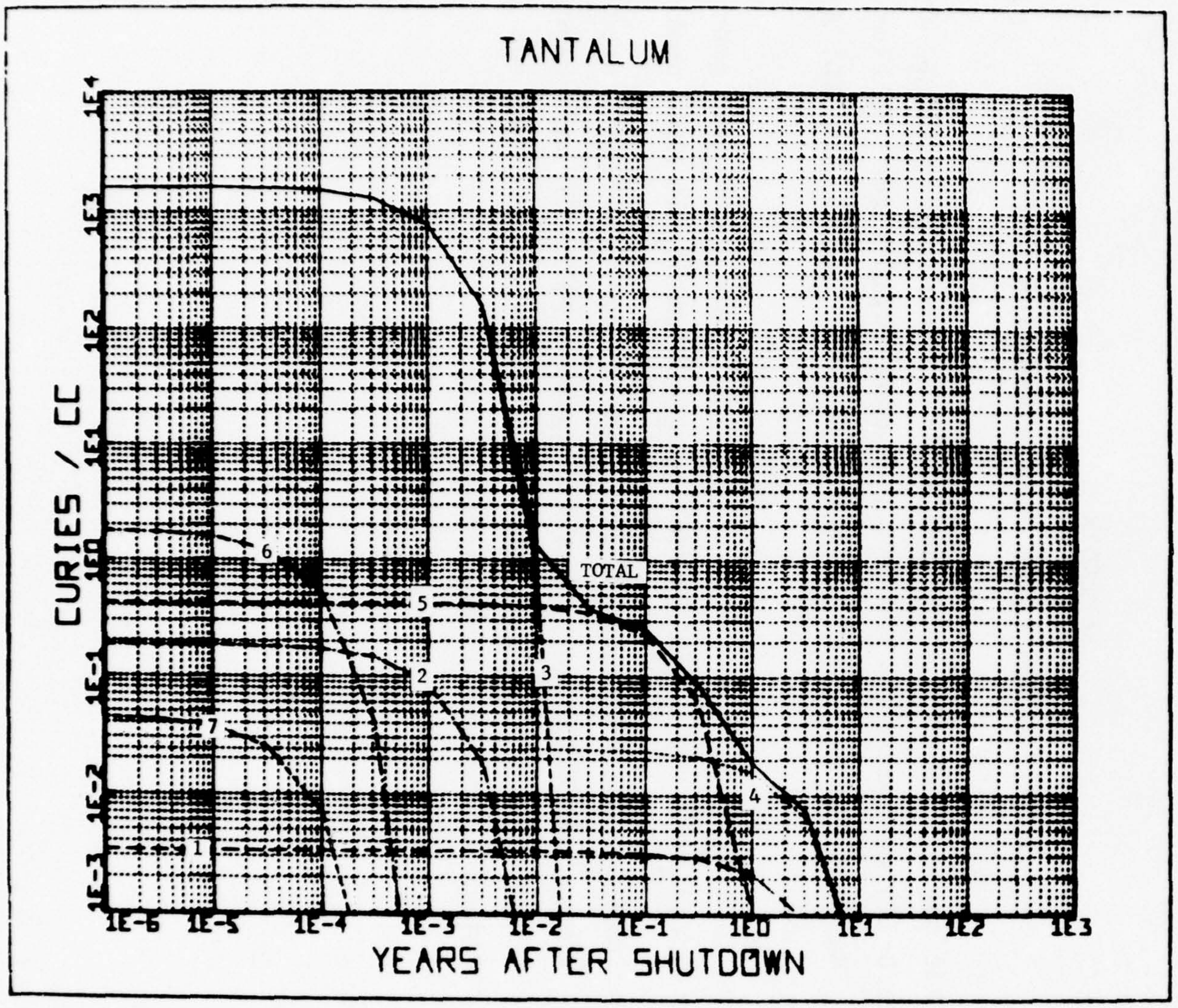

Fig. B-19 Radioactive Decay Curves for Ta

APPENDIX C

DECAY CURVES - ONE YEAR ACTIVATION

This appendix contains the radioactive decay curves (Figs. C-1 through C-19) generated by the computer code ACTALOY for 19 elements: Mg, Al, Si, P, S, K, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ag, Mo, Nb, and Ta.

The data simulates the activity derived from a one year continuous irradiation by a 10^{15} n/(cm^2-sec) flux of 14 MeV neutrons.

The number adjacent to a curve refers to the reaction listed for the element in Table 1. The solid curve labeled "Total" represents the expected activity for an element obtained from the sum of its individually numbered isotope reactions.

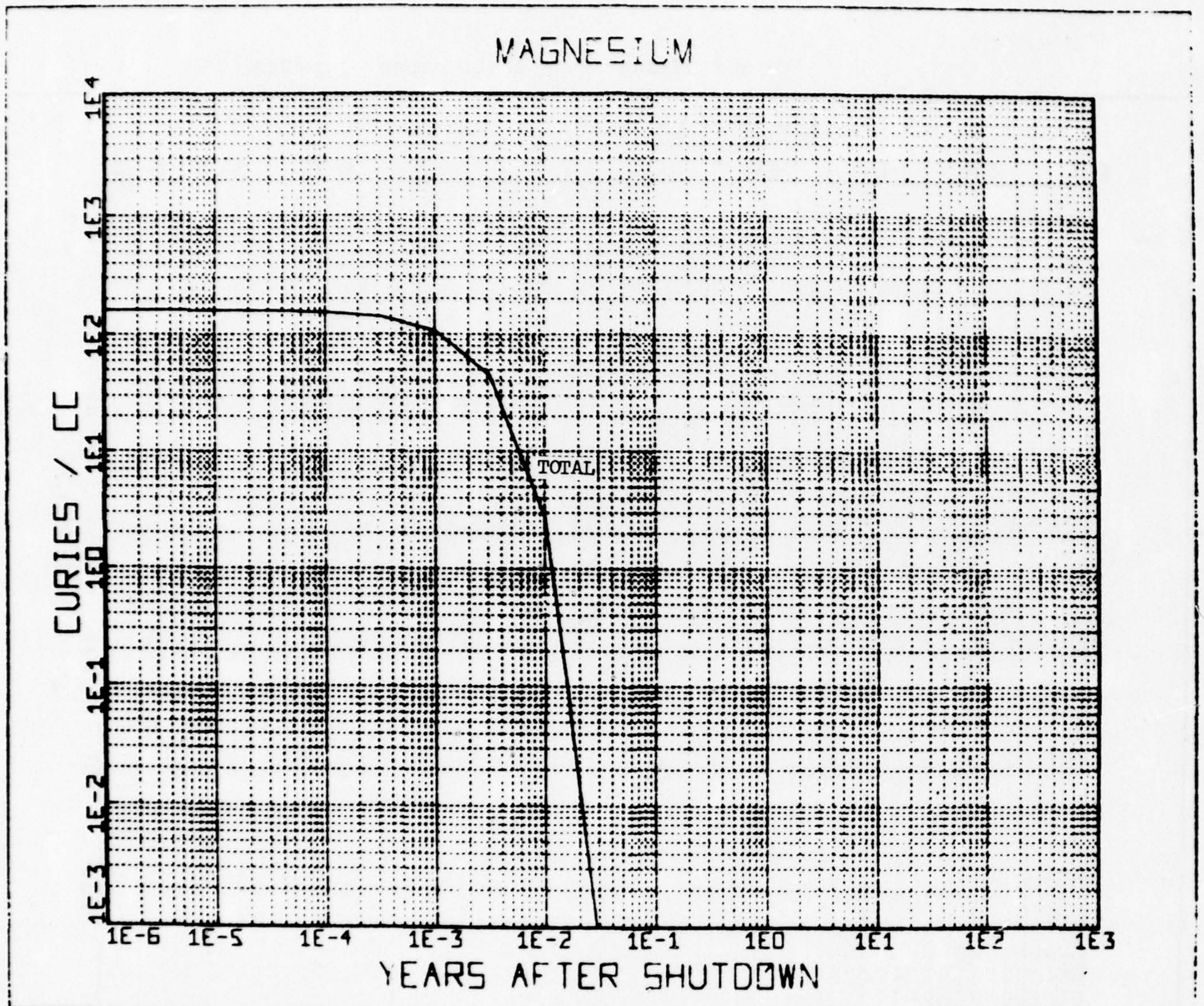

Fig. C-1 Radioactive Decay Curves for Mg

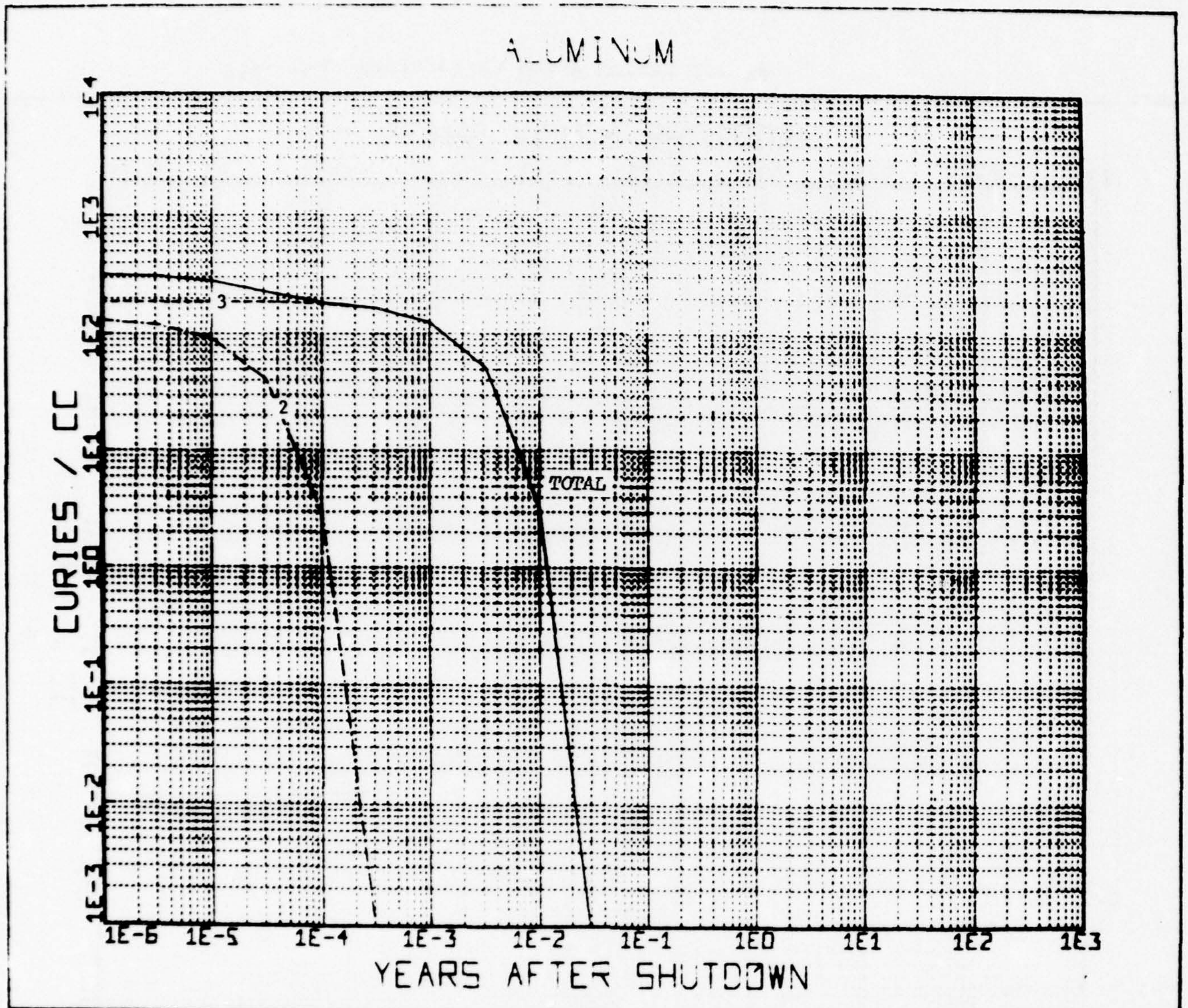

Fig. C-2 Radioactive Decay Curves for Al

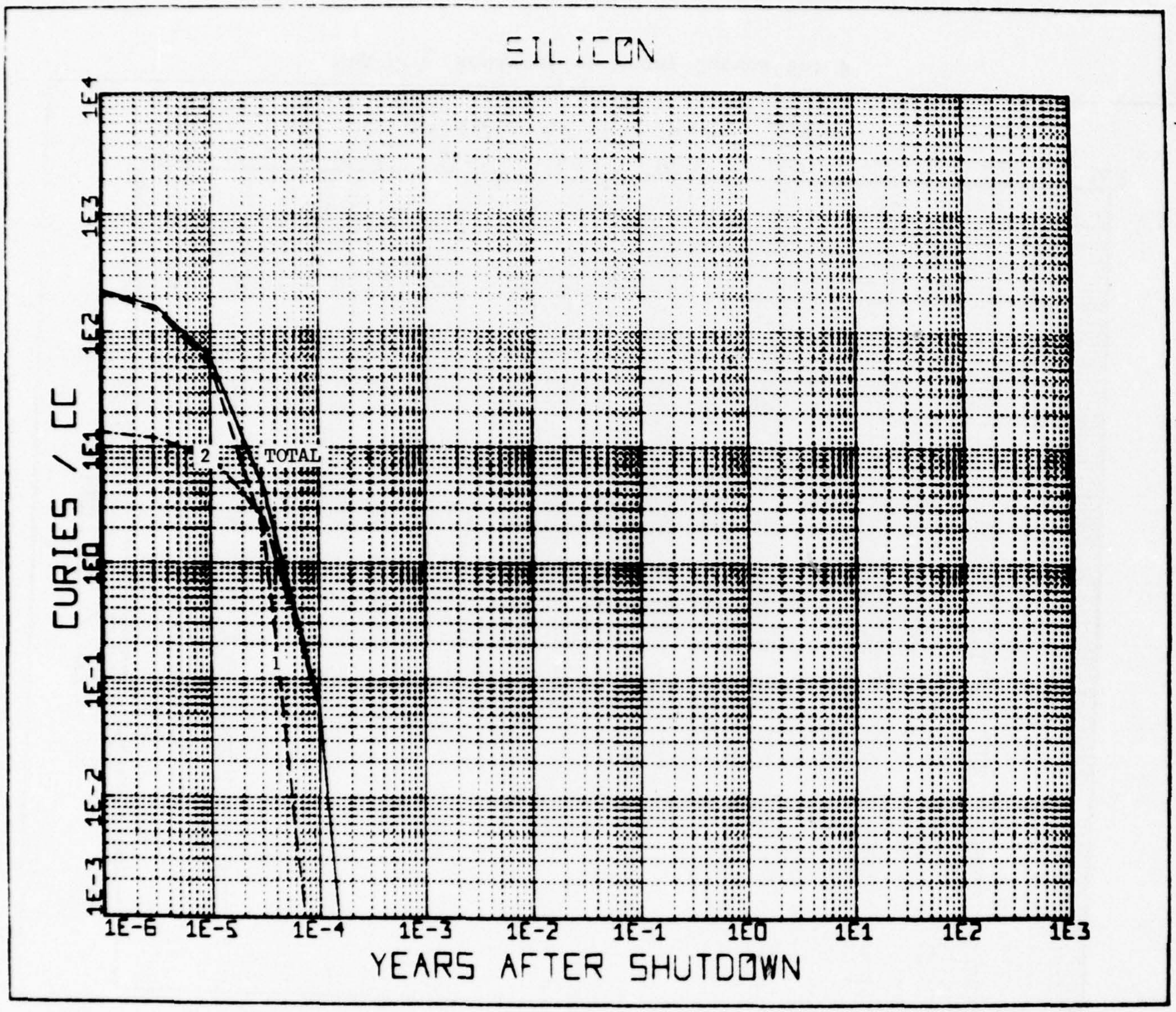

Fig. C-3 Radioactive Decay Curves for Si

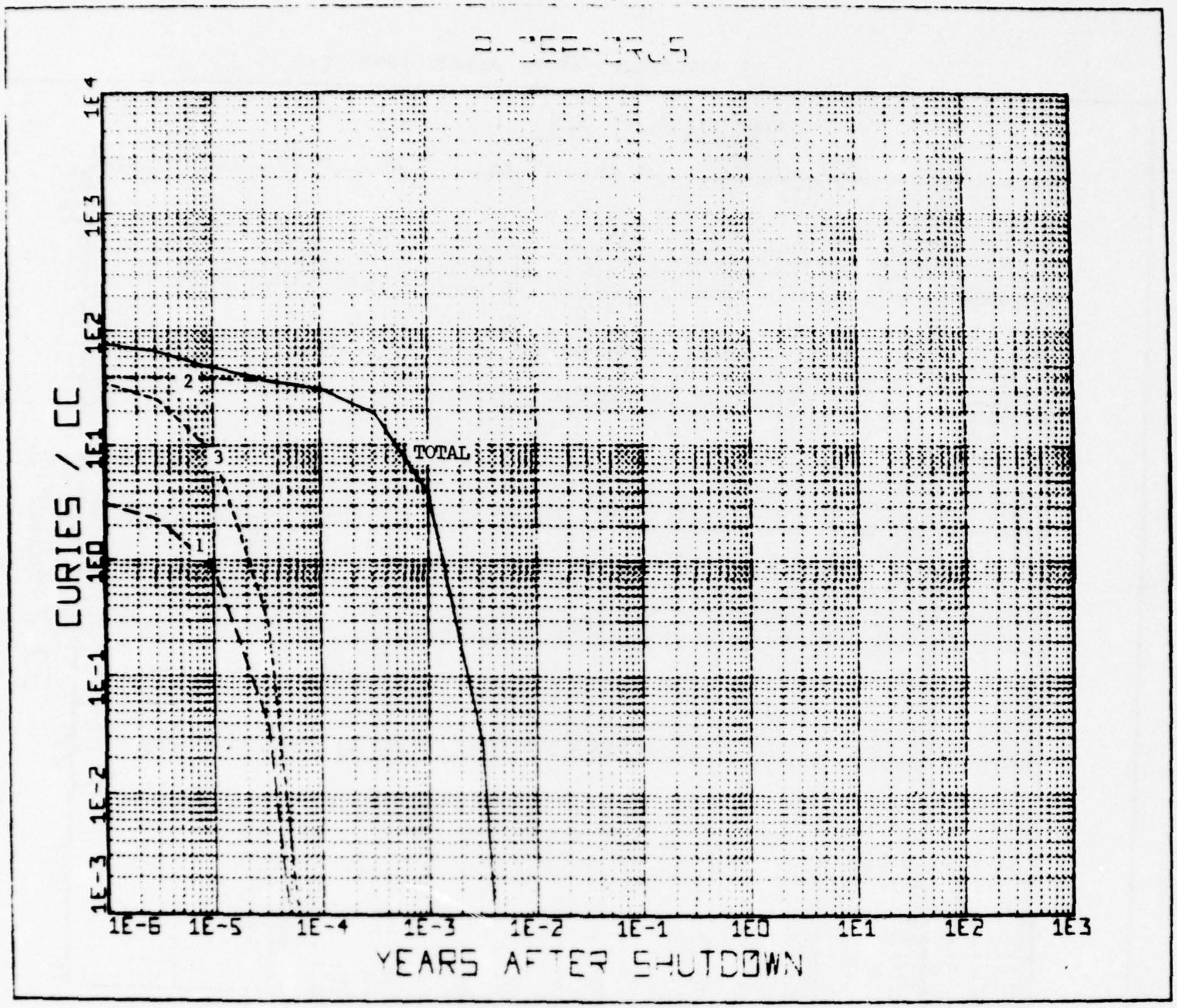

Fig. C-4 Radioactive Decay Curves for P

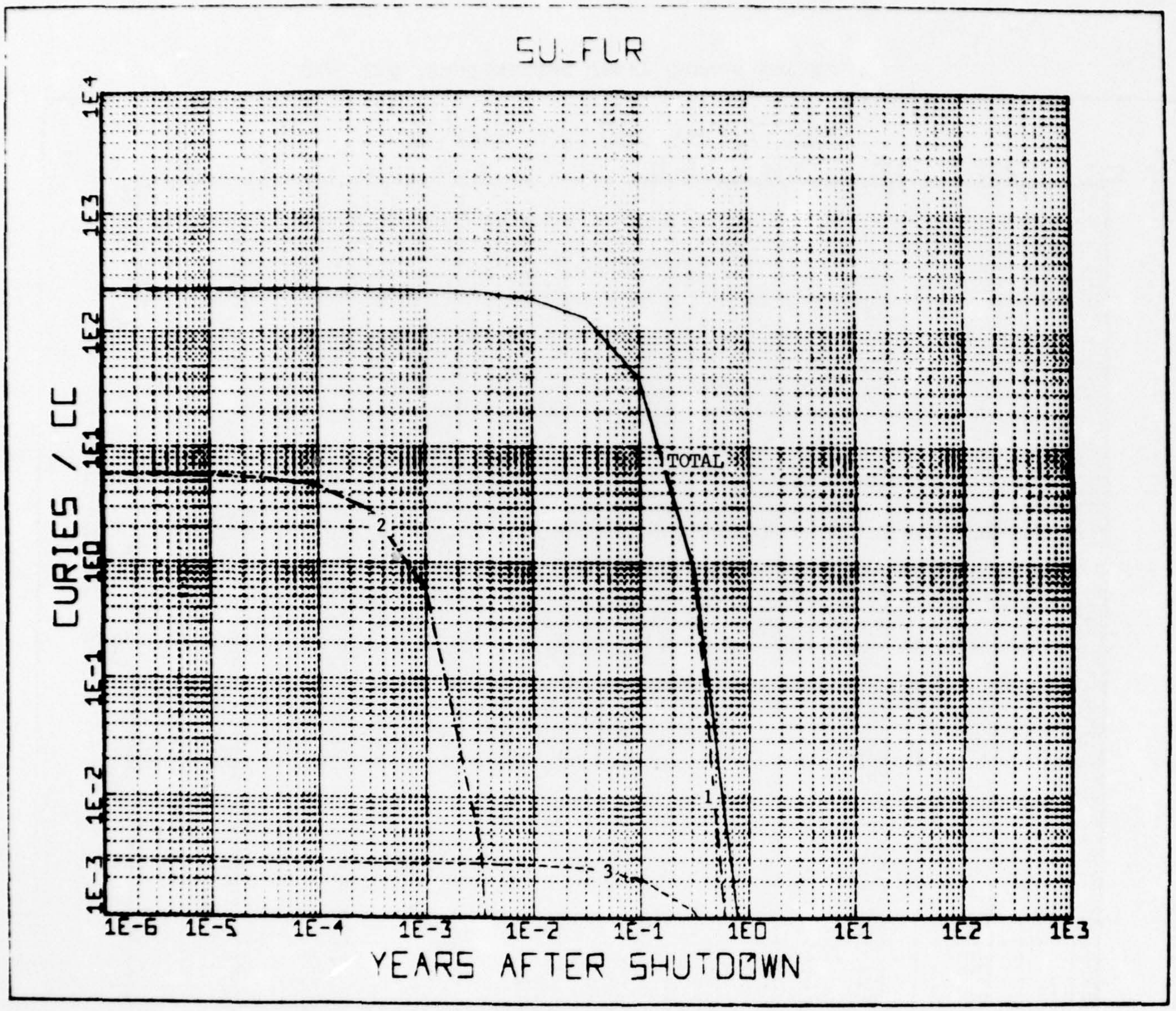

Fig. C-5 Radioactive Decay Curves for S

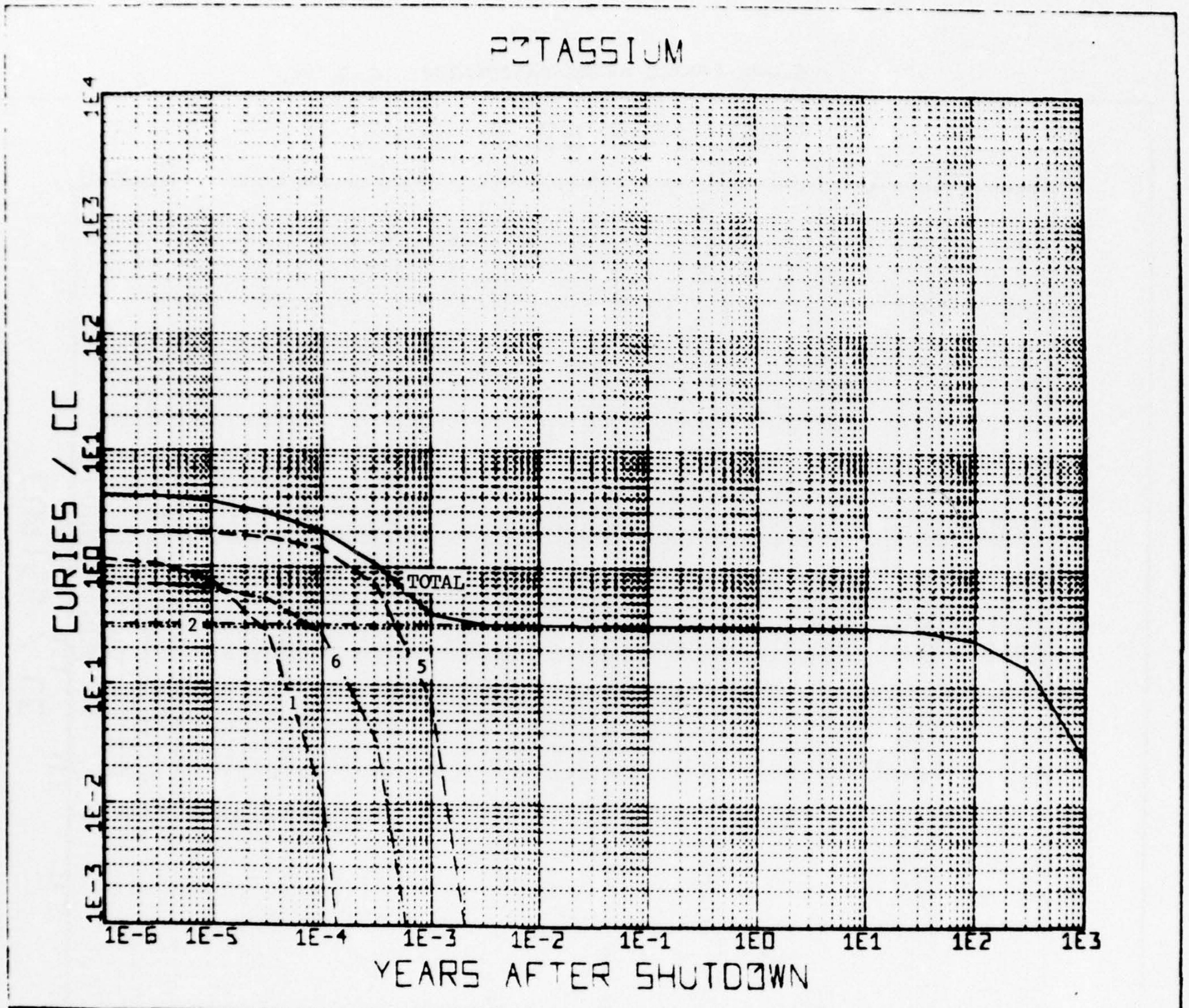

Fig. C-6 Radioactive Decay Curves for K

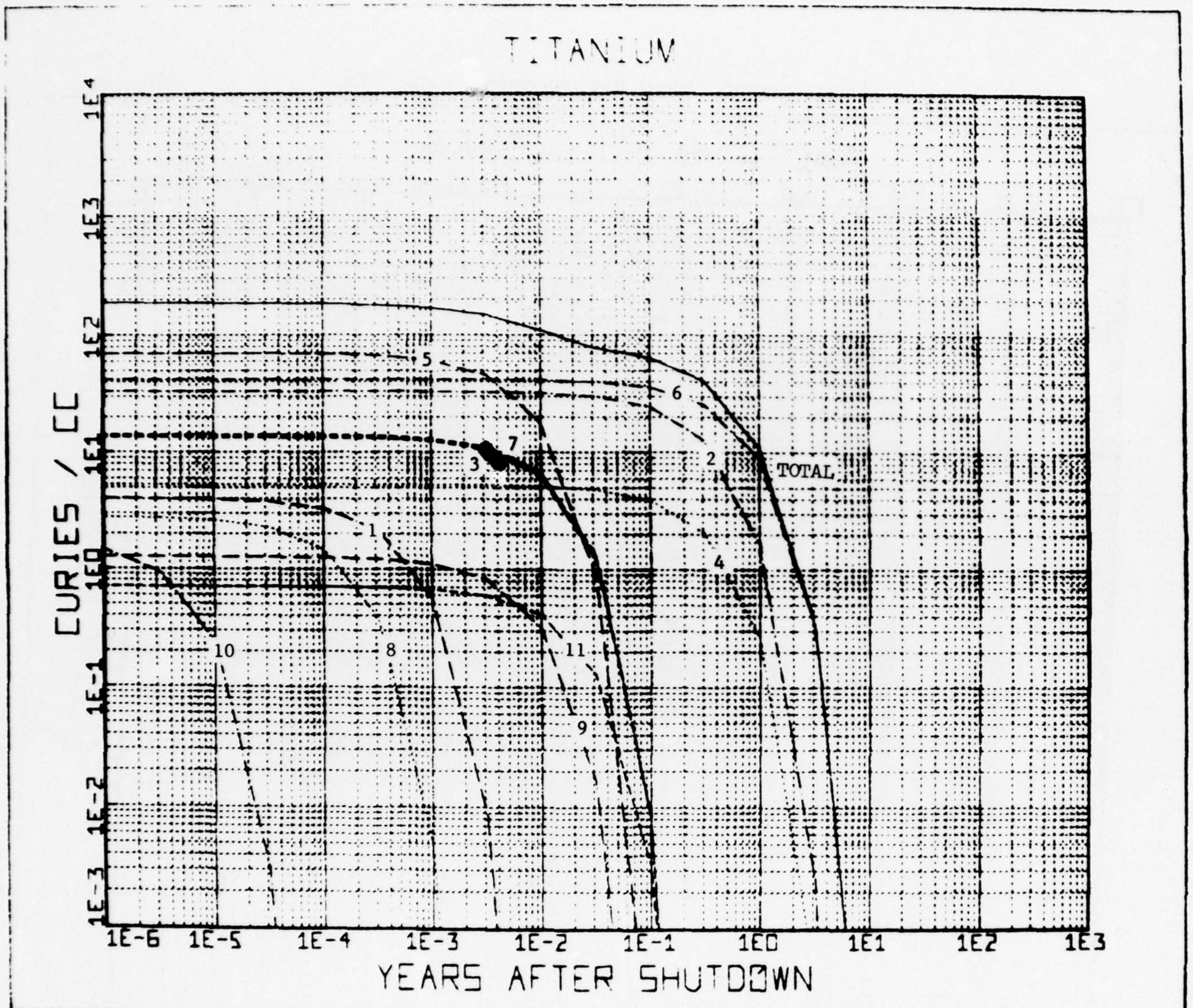

Fig. C-7 Radioactive Decay Curves for Ti

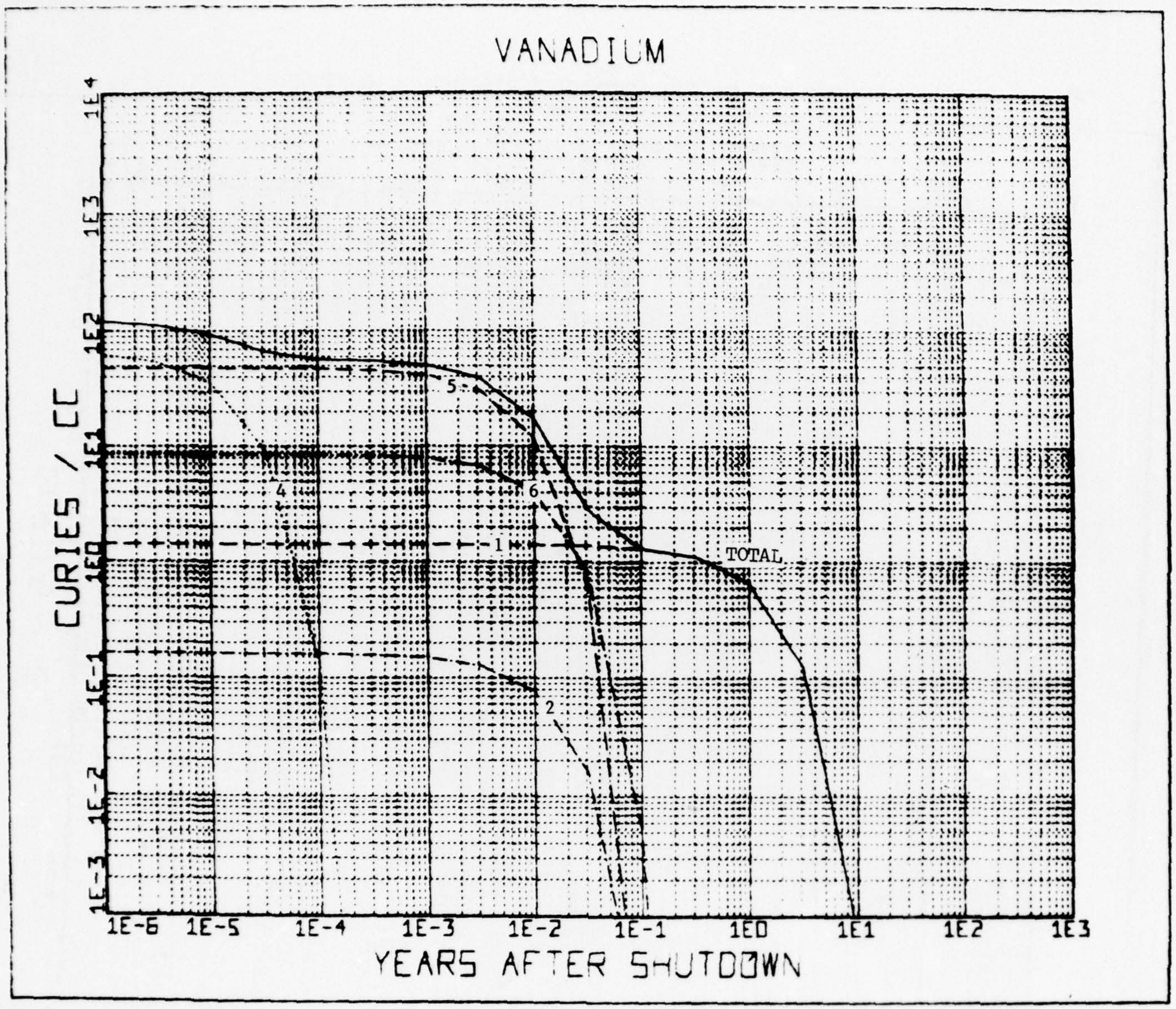

Fig. C-8 Radioactive Decay Curves for V

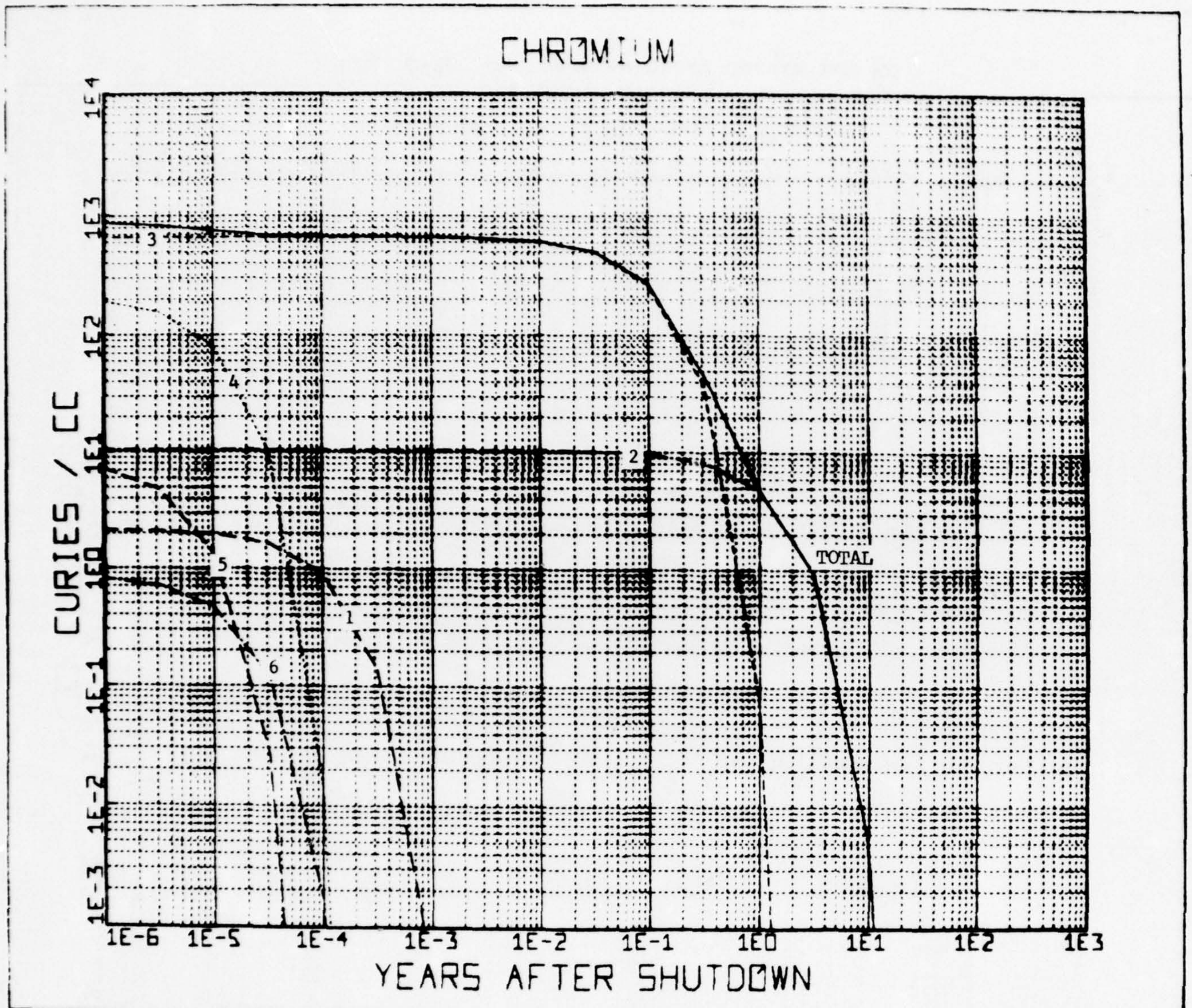

Fig. C-9 Radioactive Decay Curves for Cr

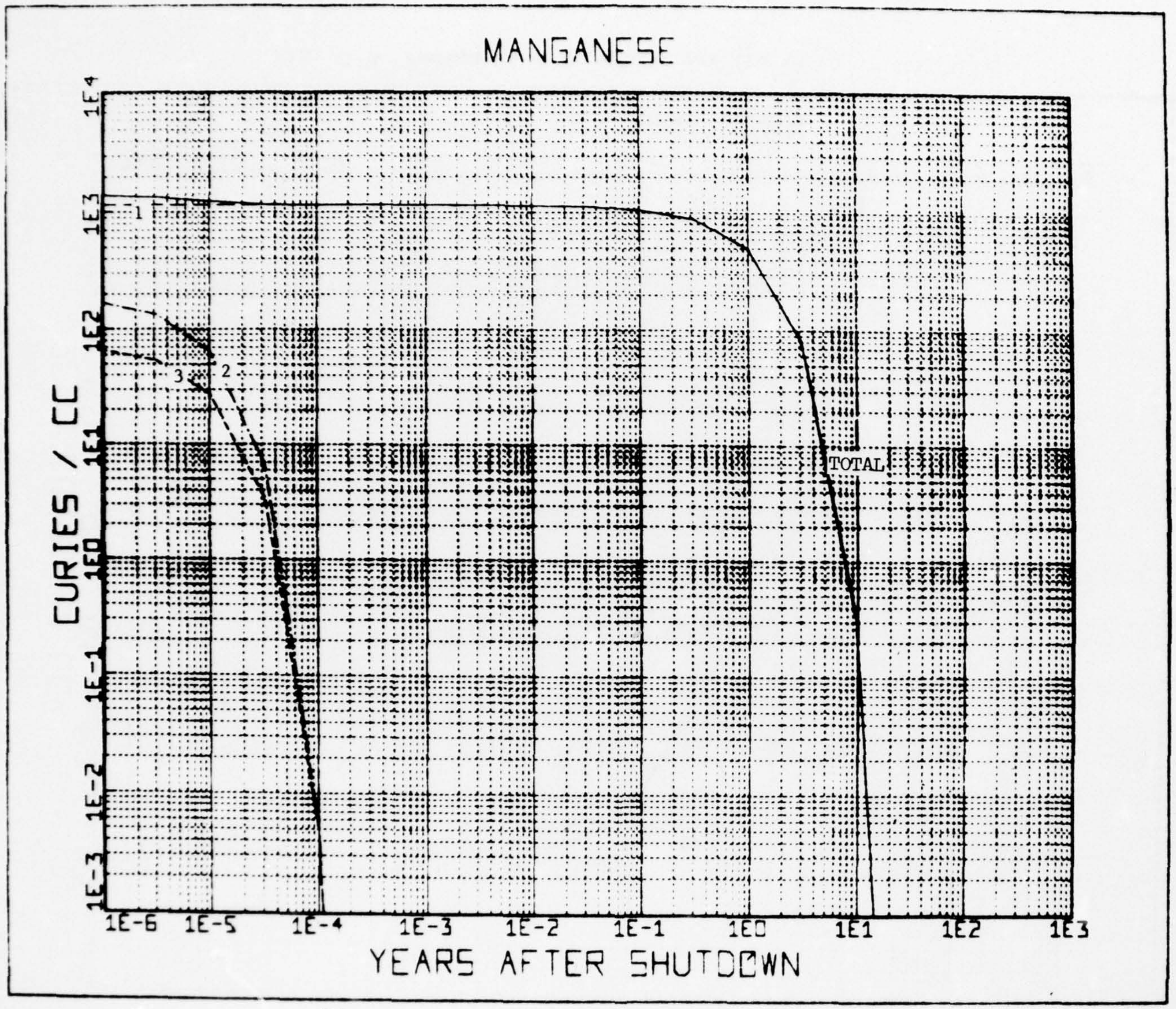

Fig. C-10 Radioactive Decay Curves for Mn

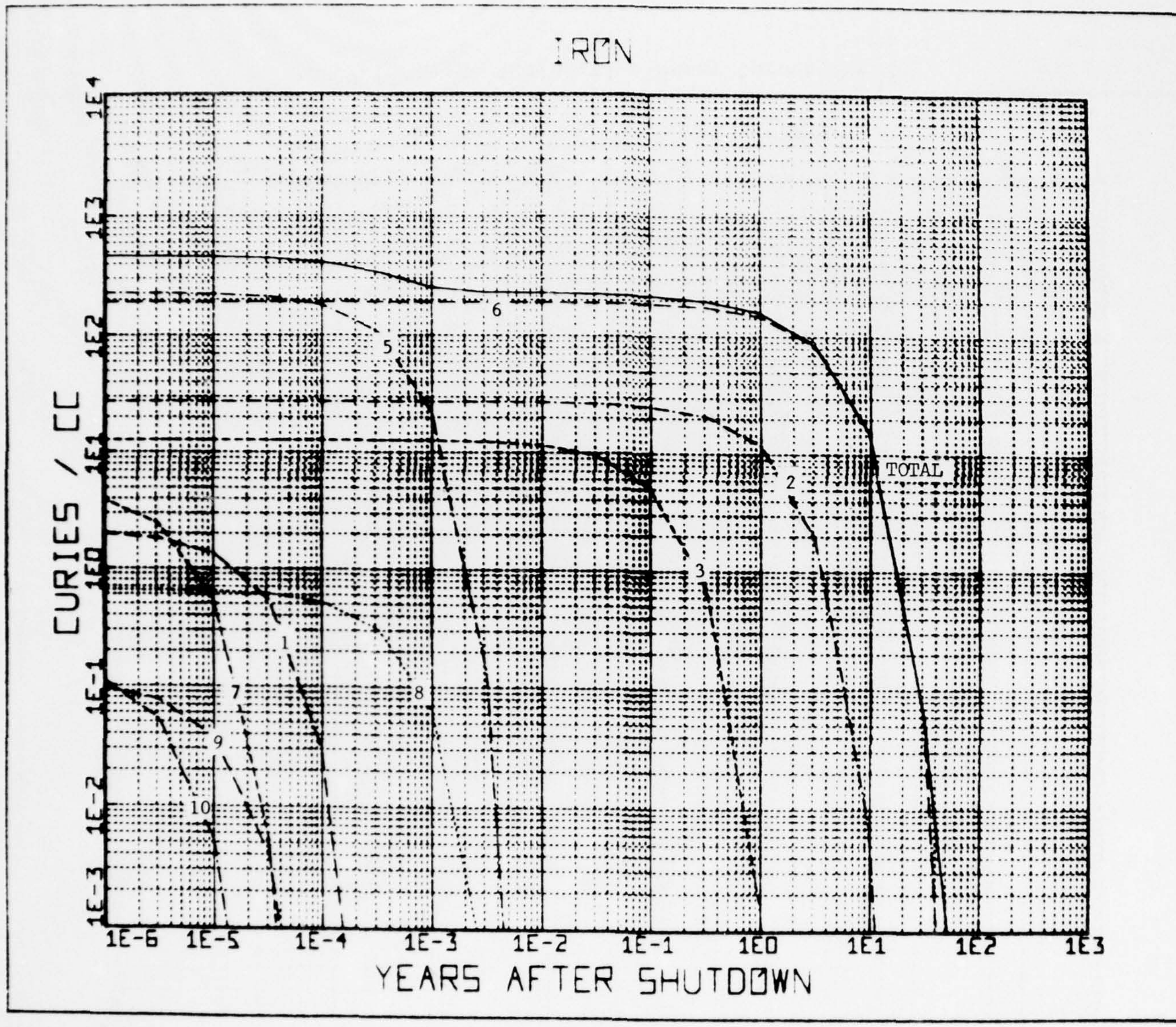

Fig. C-11 Radioactive Decay Curves for Fe

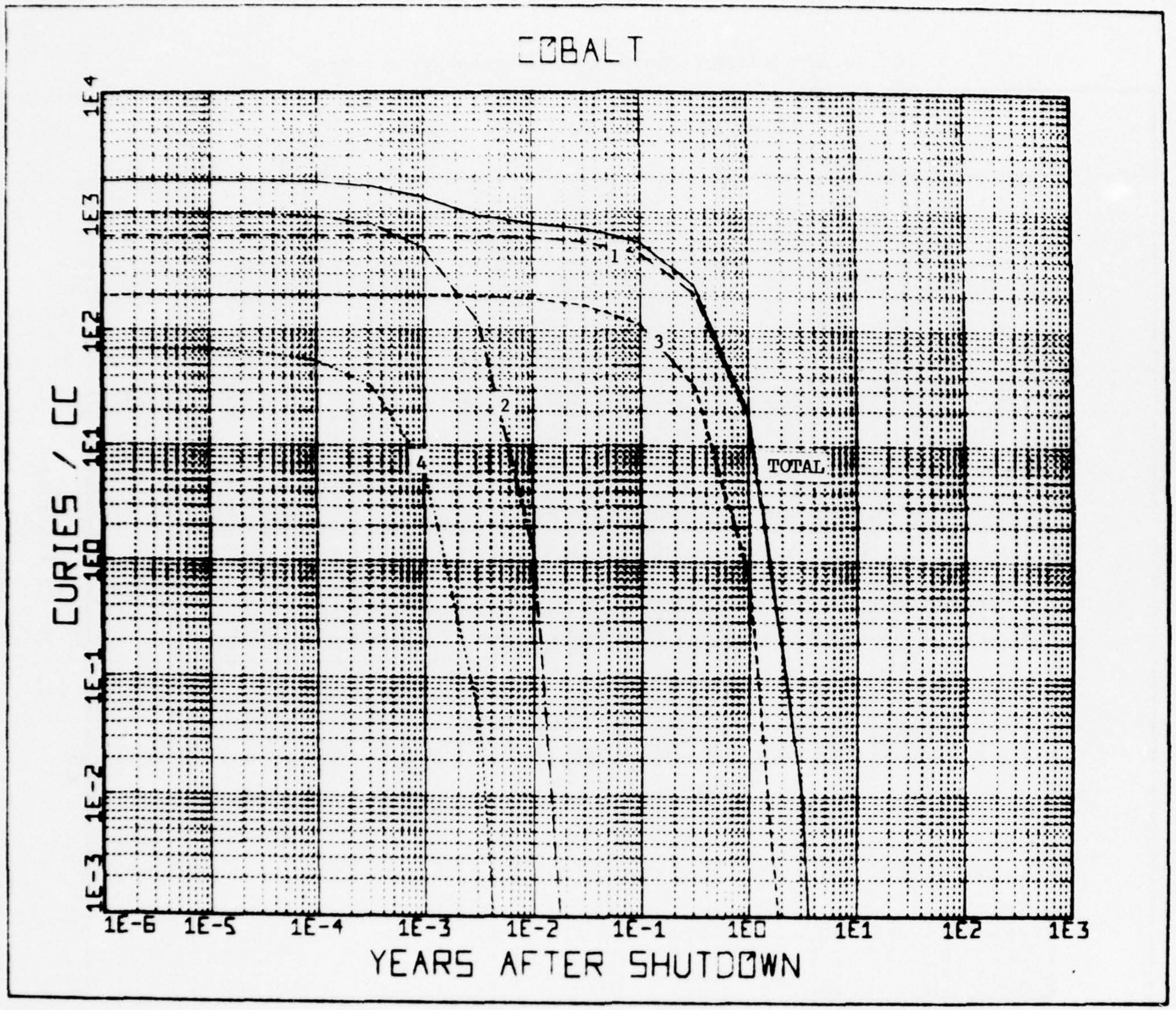

Fig. C-12 Radioactive Decay Curves for Co

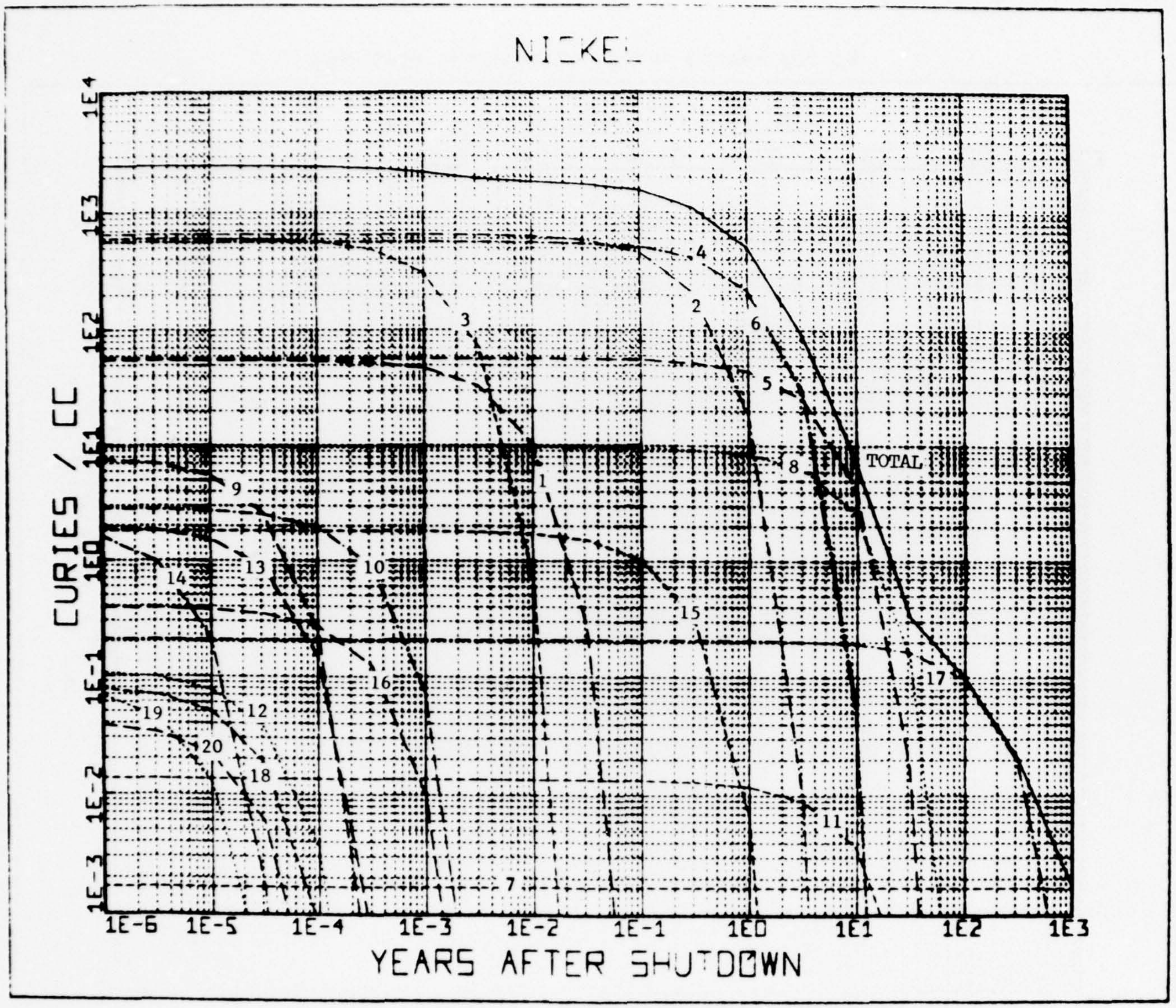

Fig. C-13 Radioactive Decay Curves for Ni

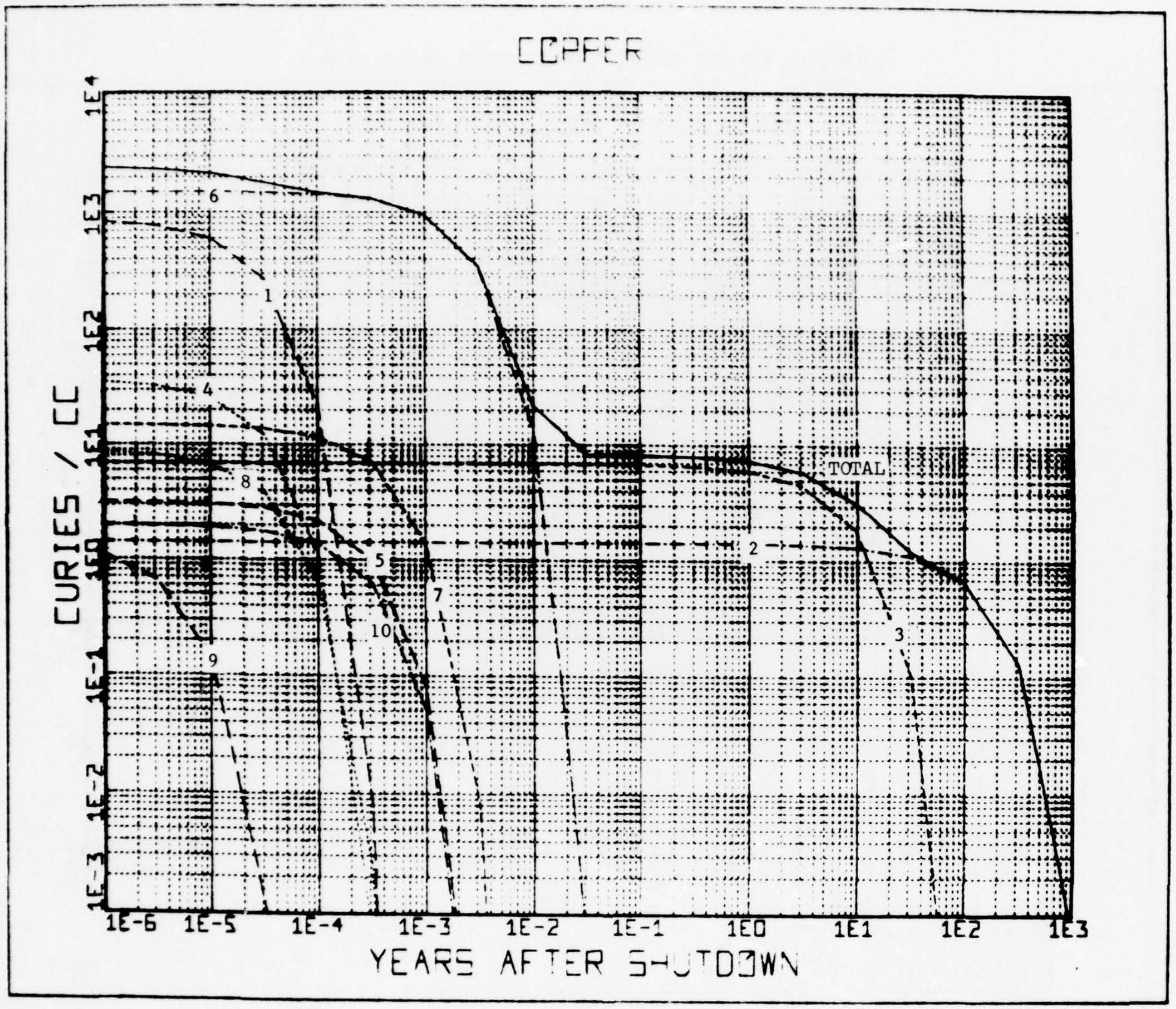

Fig. C-14 Radioactive Decay Curves for Cu

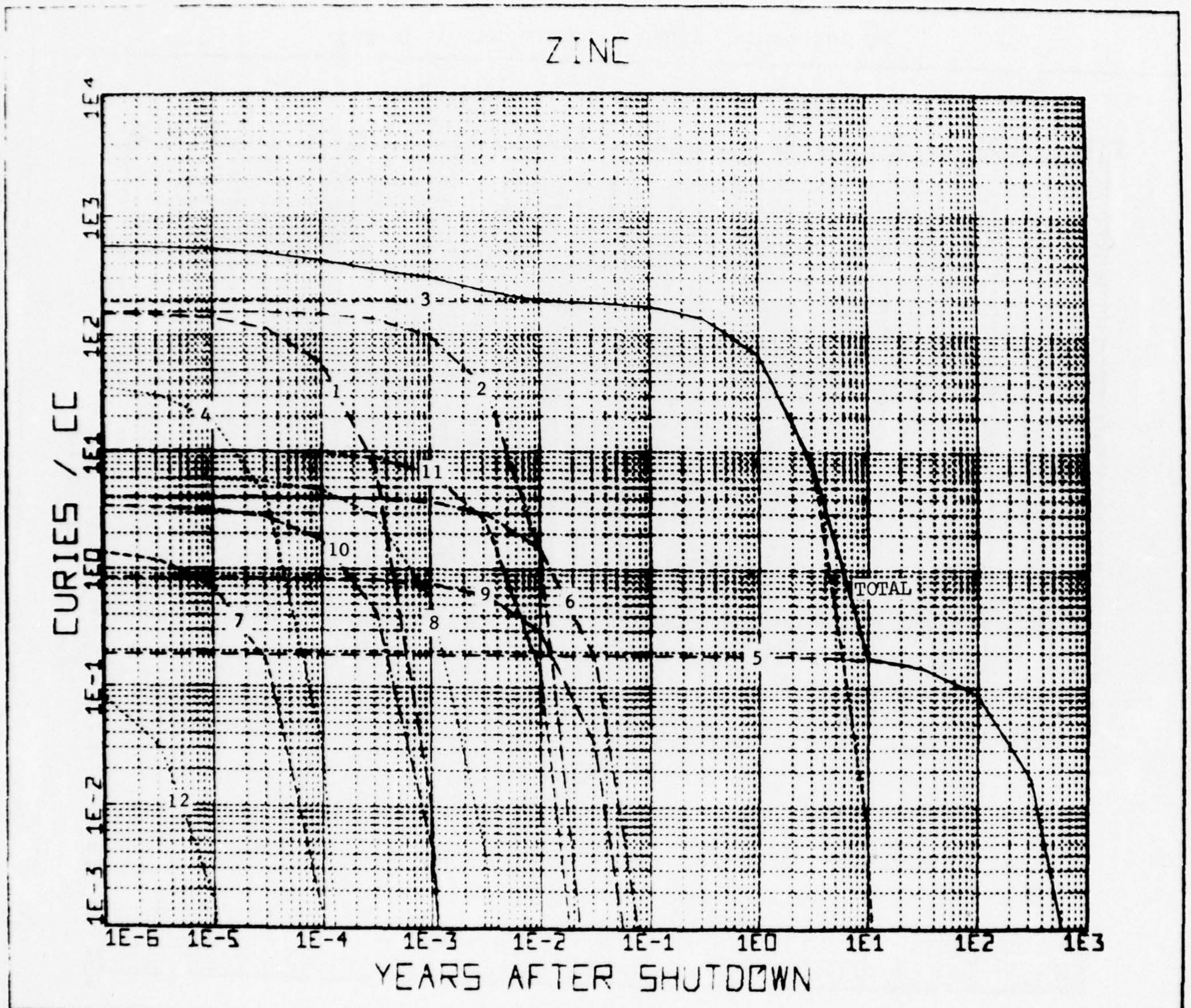

Fig. C-15 Radioactive Decay Curves for Zn

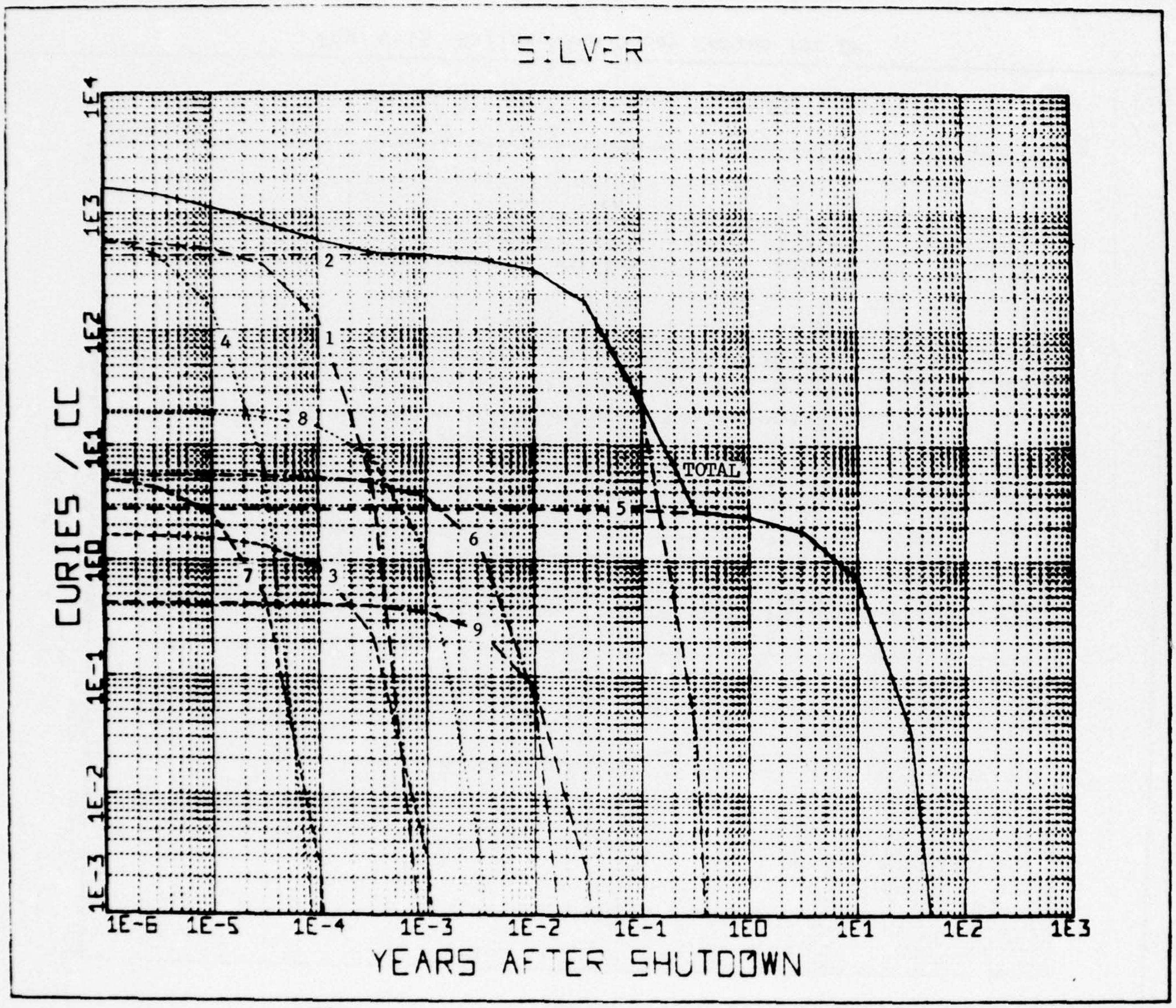

Fig. C-16 Radioactive Decay Curves for Ag

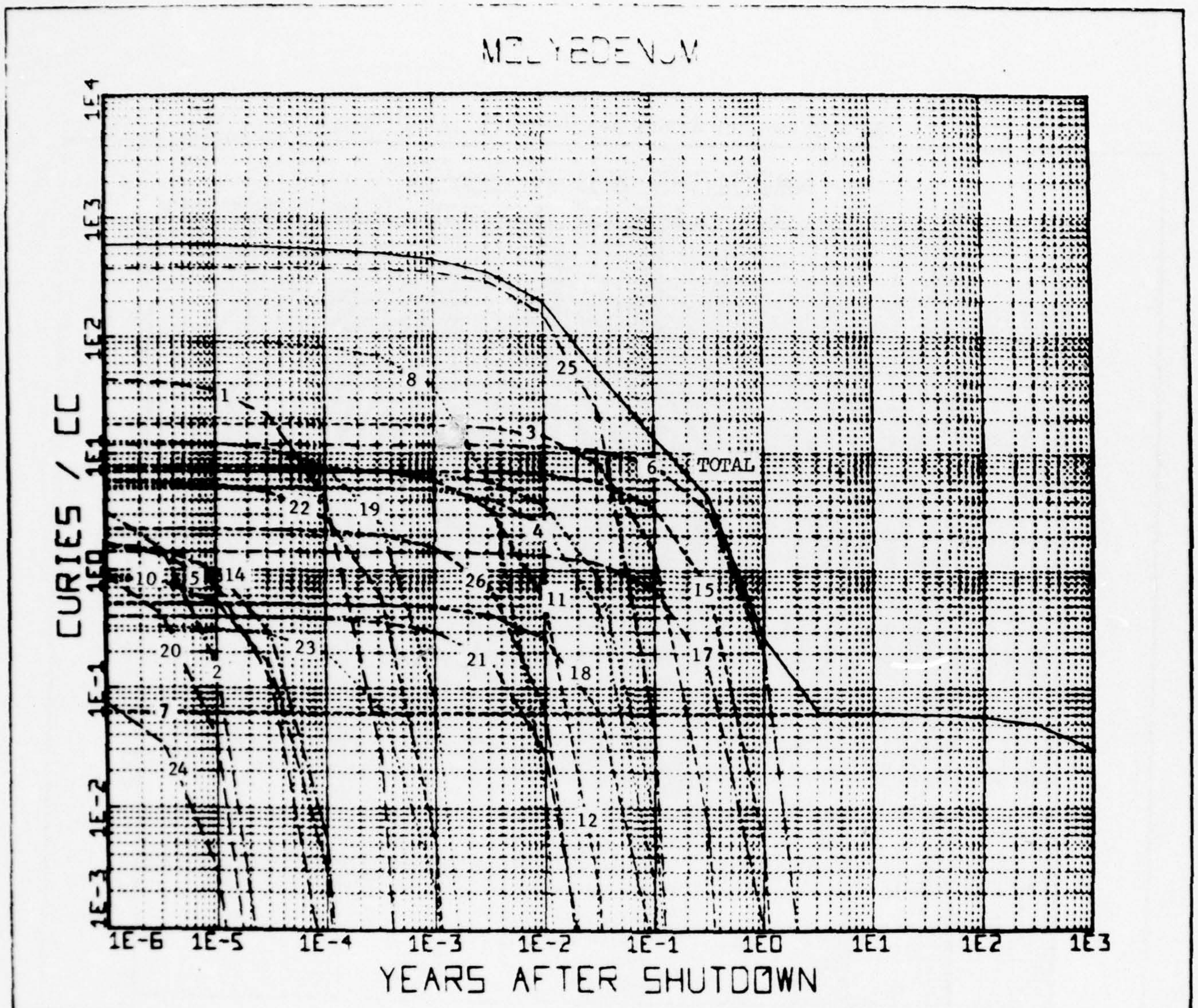

Fig. C-17 Radioactive Decay Curves for Mo

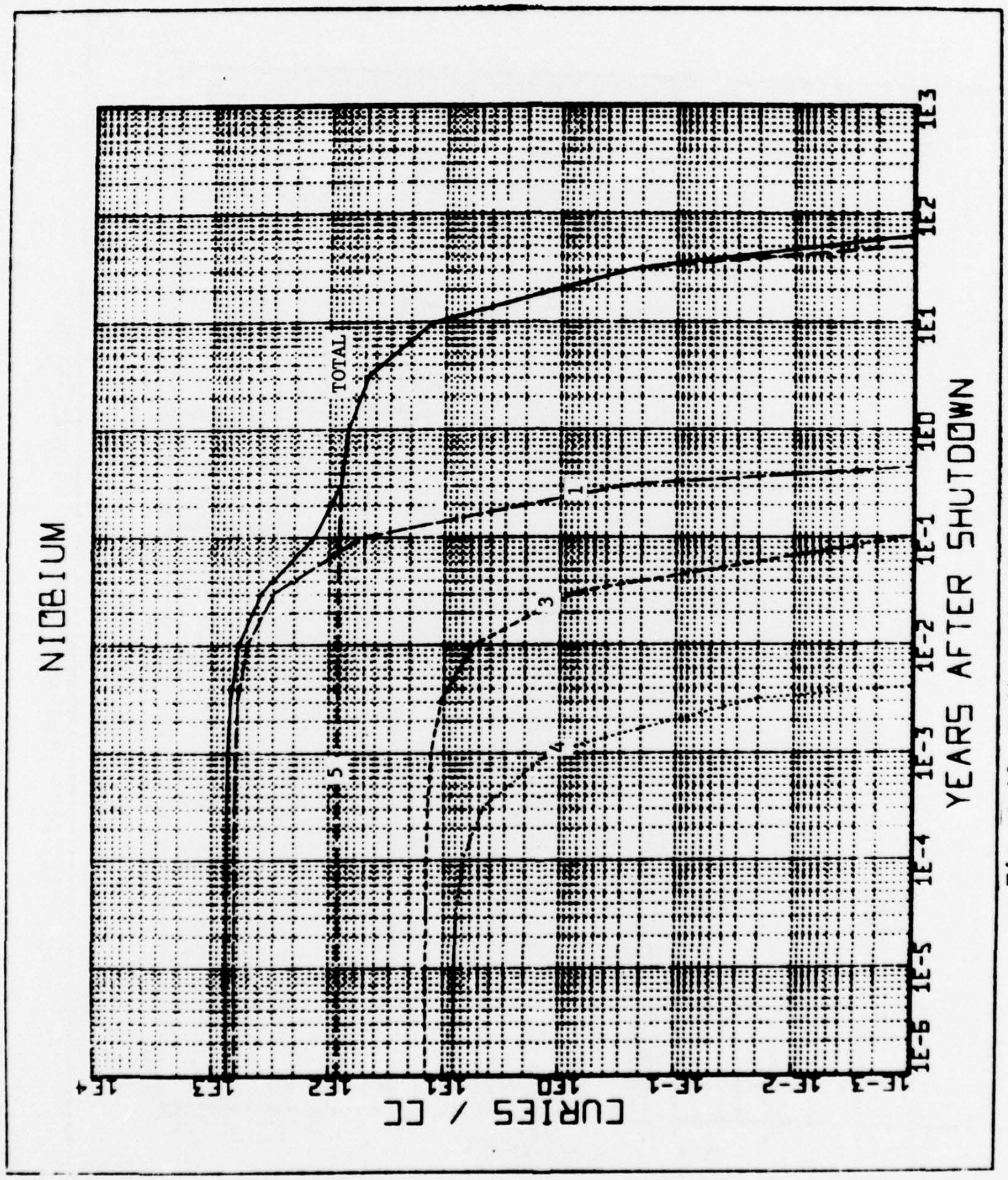

Fig. C-18 Radioactive Decay Curves for Nb

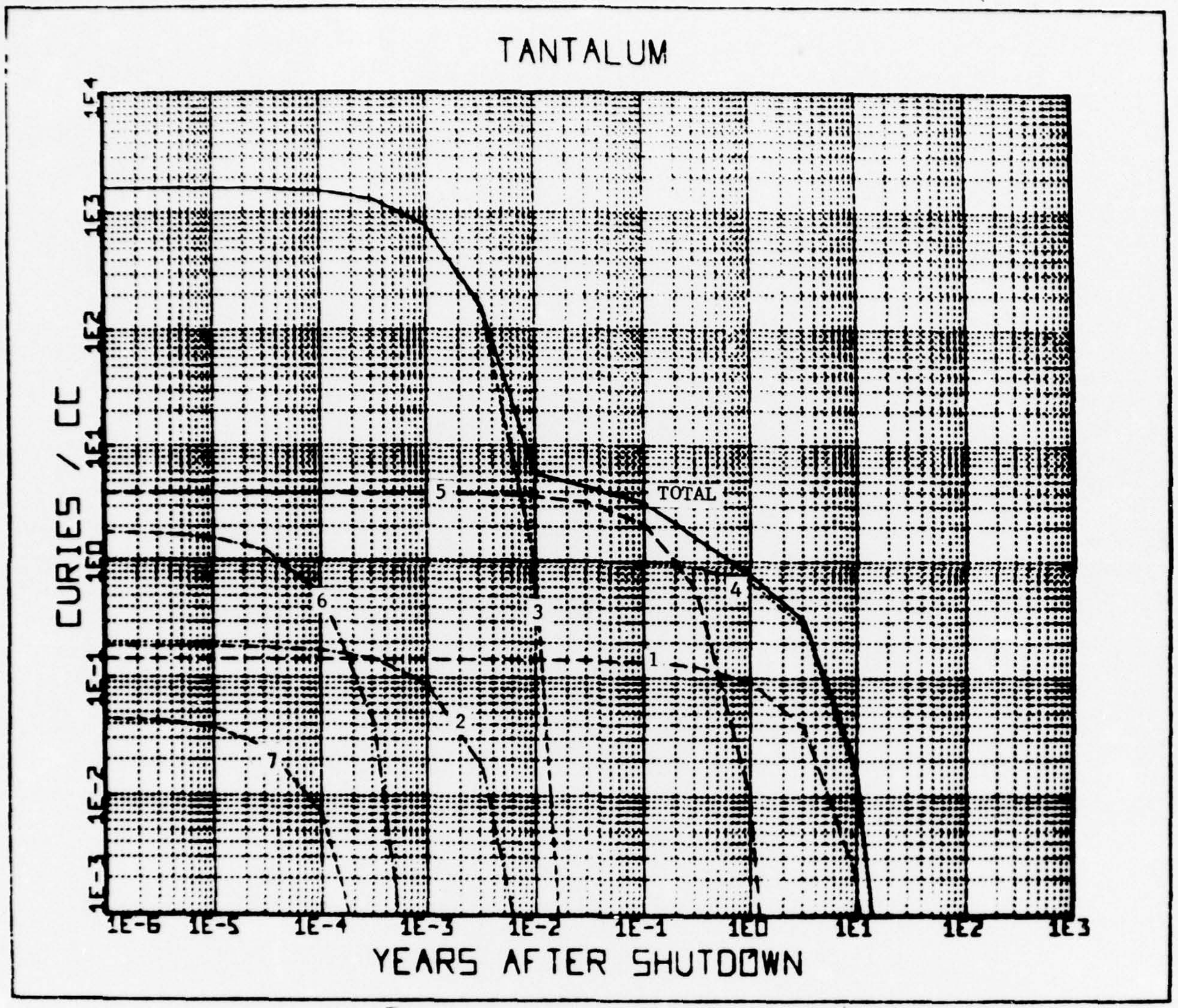

Fig. C-19 Radioactive Decay Curves for Ta